CERN program and plans for the European Strategy

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Director Research and Computing

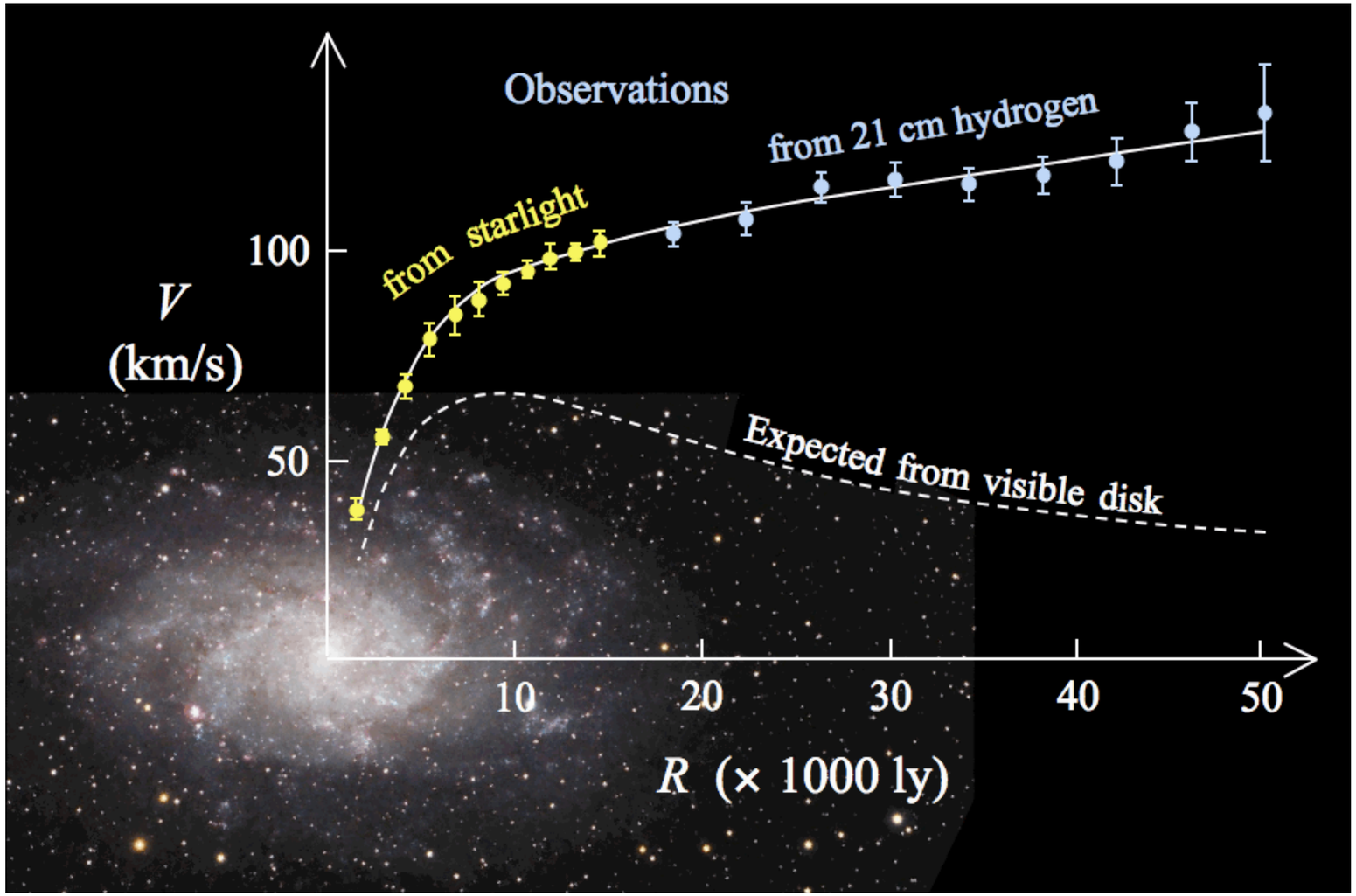
APS DPF Meeting, Fermilab, July 31 - Aug 4, 2017

There must be more than the Standard Model…

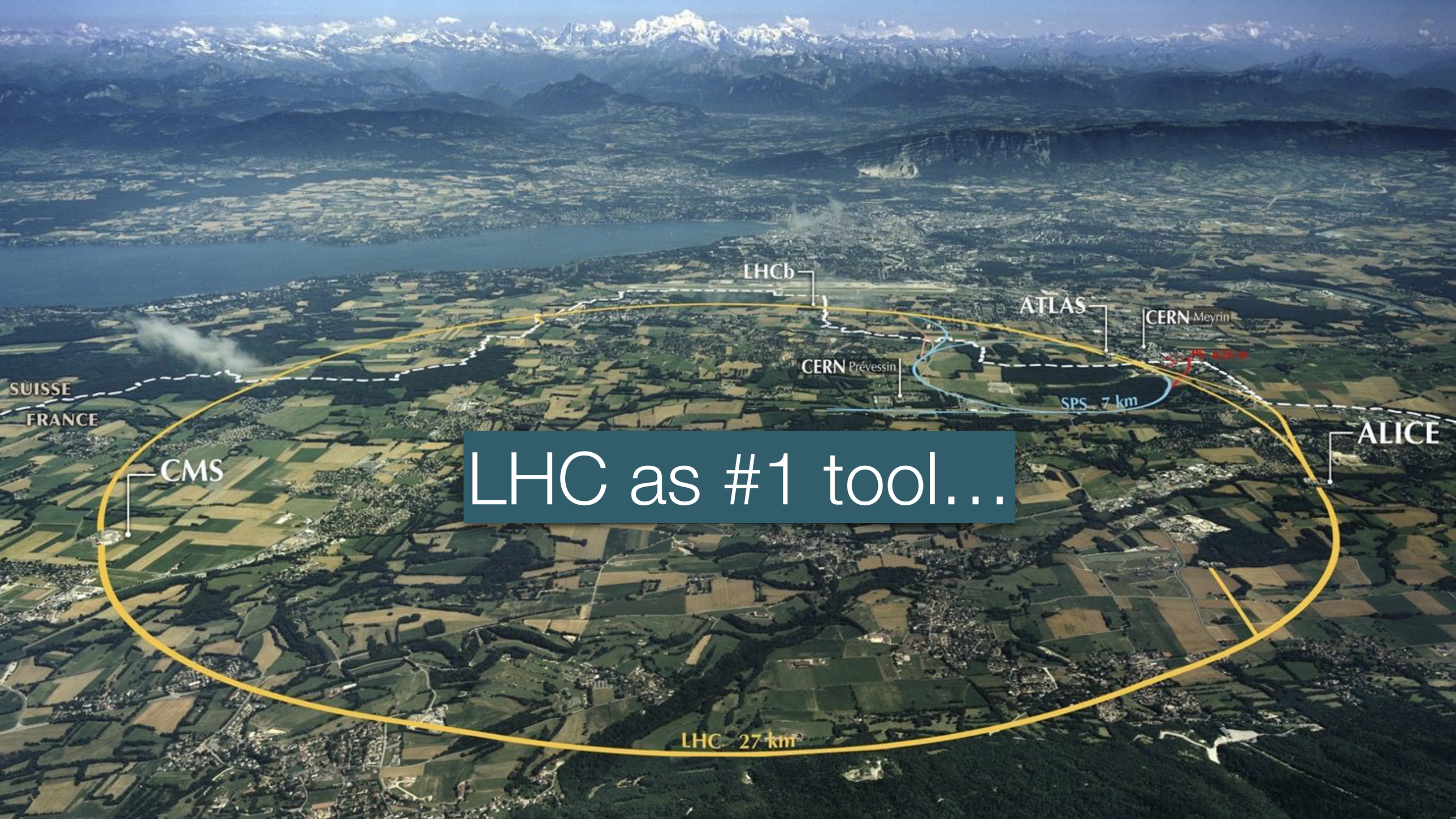
Rotational Curves of Galaxies

- Outer rim of galaxies is seen to rotate faster than expected from Newtonian mechanics
  - there is more mass than is seen interacting

Dark Matter

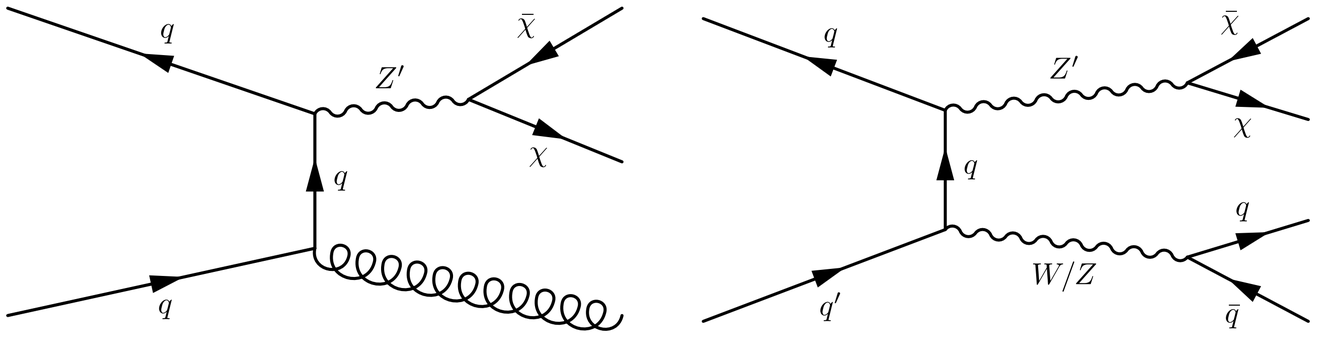


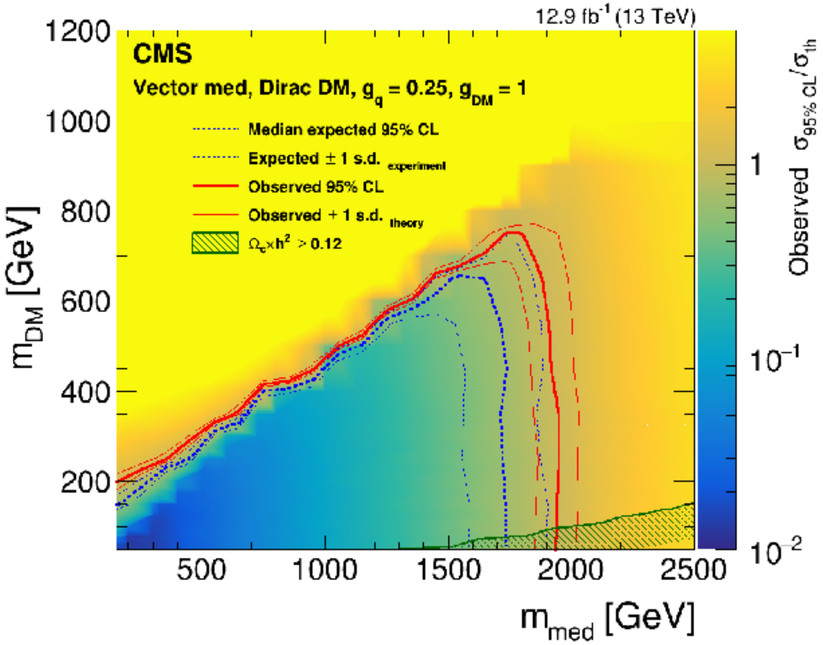
…executing the ongoing (worldwide) Strategy for Particle Physics

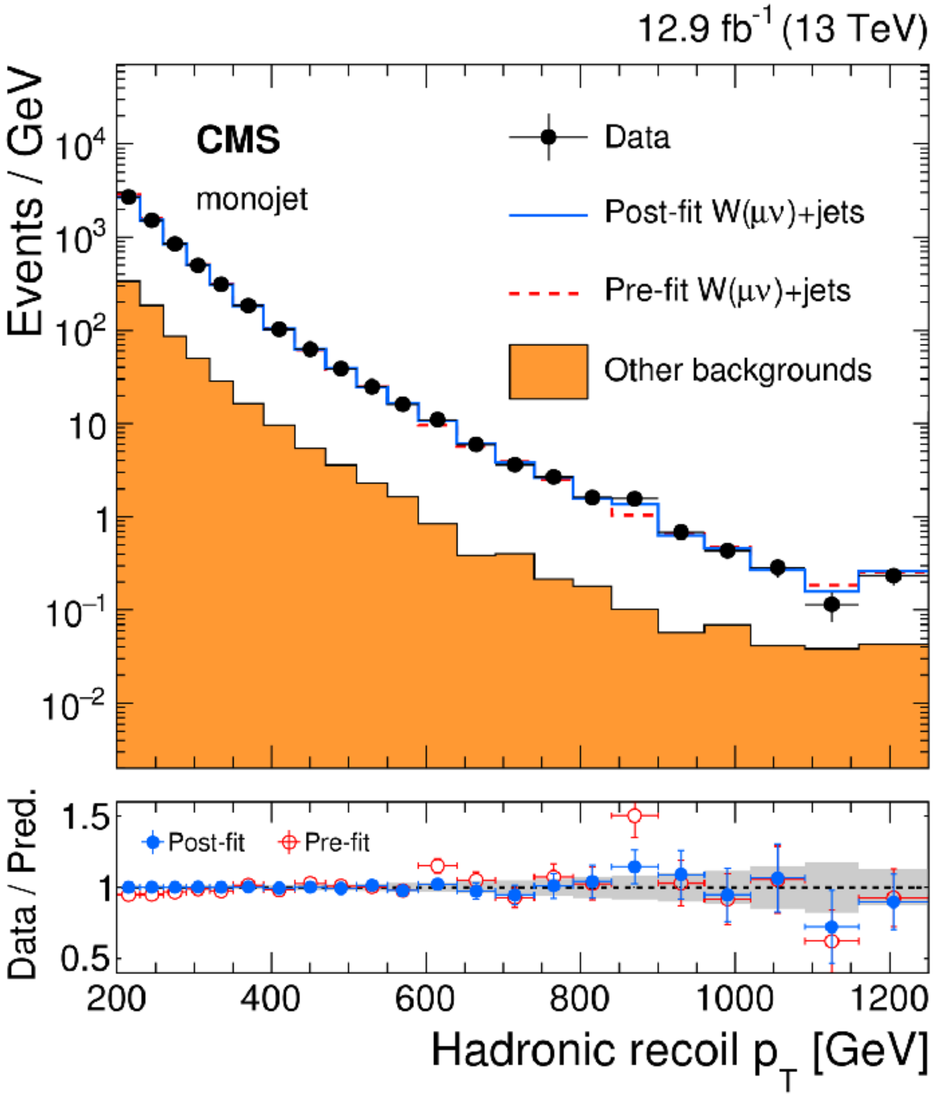

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

LHC as #1 tool…

Example of Dark Matter Search at the LHC





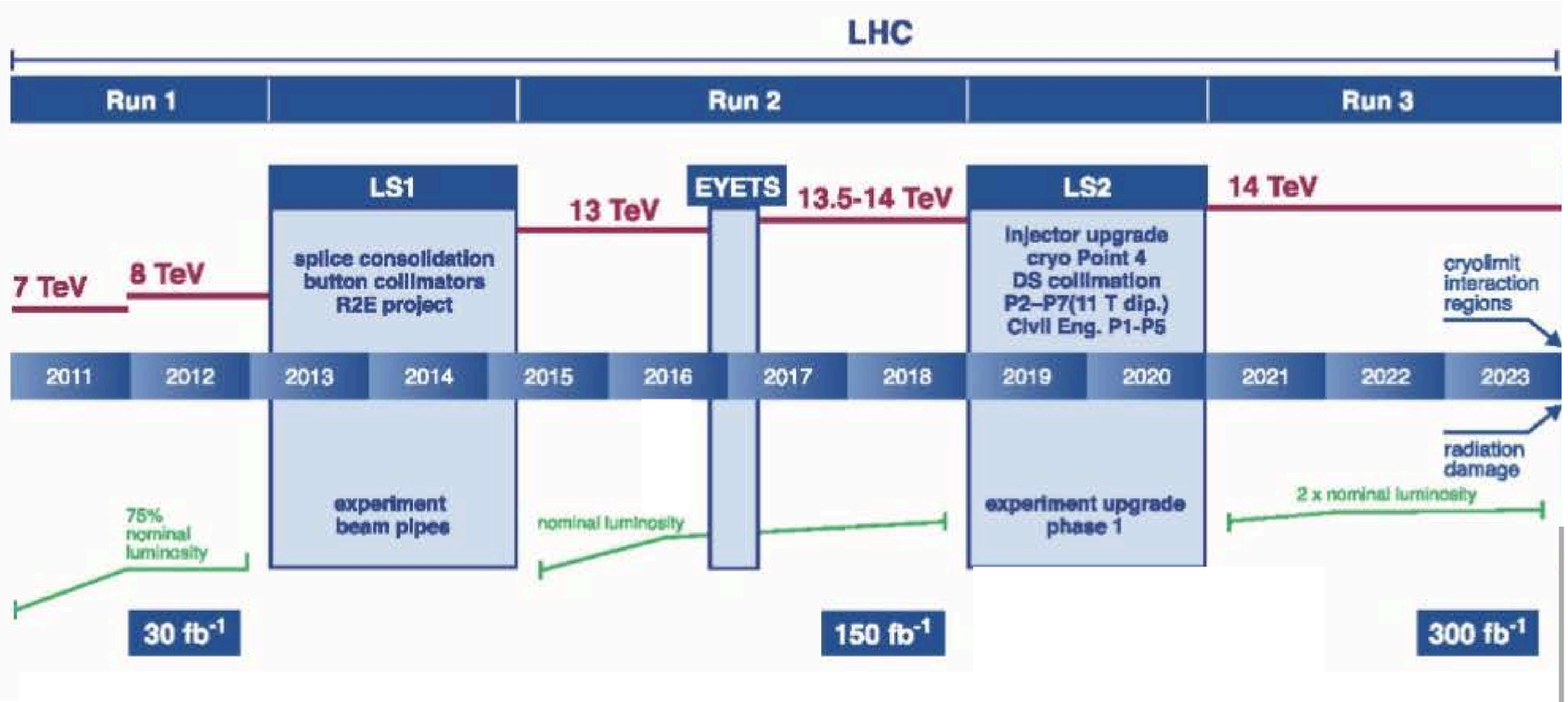


Goal of LHC – Identify the Physics beyond the Standard Model

- Explore an energy regime that has not been chartered before
  - have entered 13 TeV regime in *production* mode
  - 14 TeV *after* LS2 and possibly 15 TeV (study group)
- Look for small deviations (small couplings) from the Standard Model
  - Precision measurements of (rare) processes
  - Higgs particle as a portal

Luminosity need in both cases

LHC schedule



HL-LHC
High
Luminosity
Phase of LHC

Substantial upgrades for
ALICE and LHCb;
preparatory upgrades for
ATLAS and CMS including
civil construction

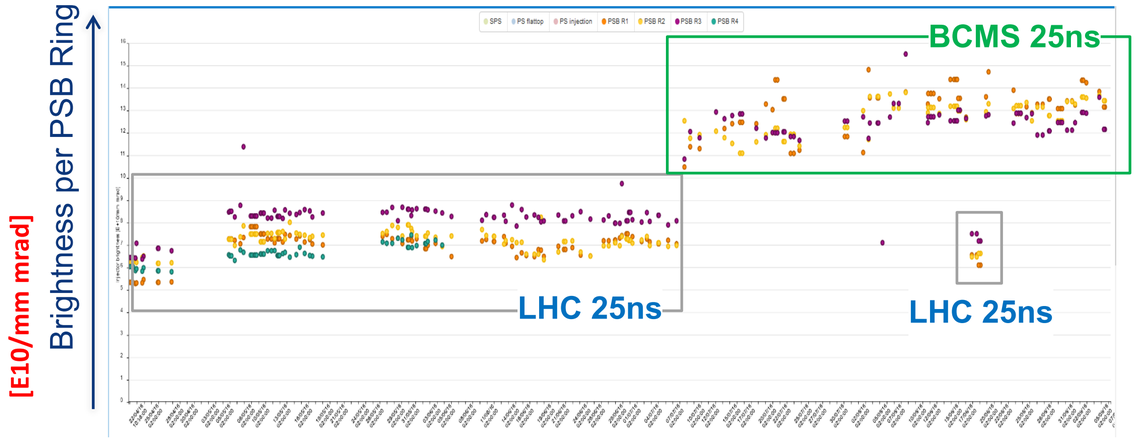
end of original LHC

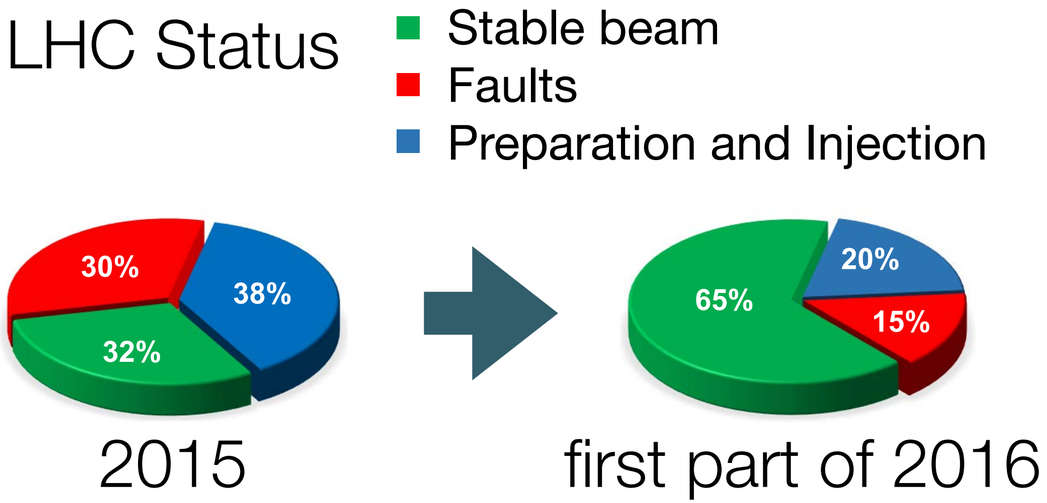
Extraordinary LHC Performance in 2016

- Batch Compression Merging and Splitting scheme is boosting bunch brightness: bunches collide more effectively → increased pile-up

- Machine availability has essentially doubled (meticulous attention to operation)

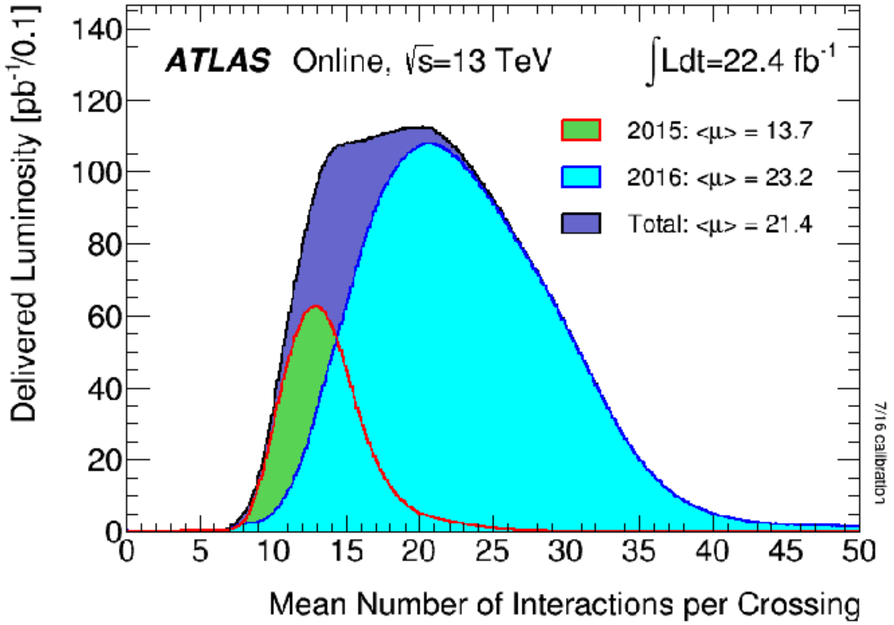
- Considerably more physics data to digest

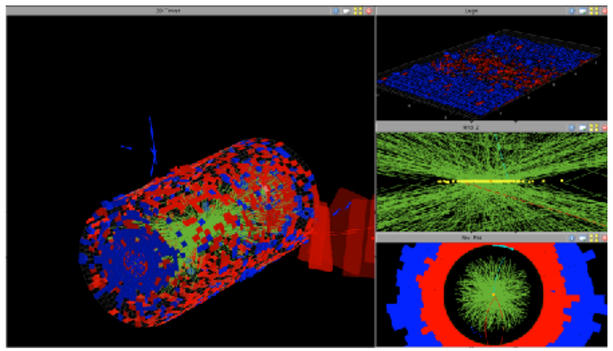


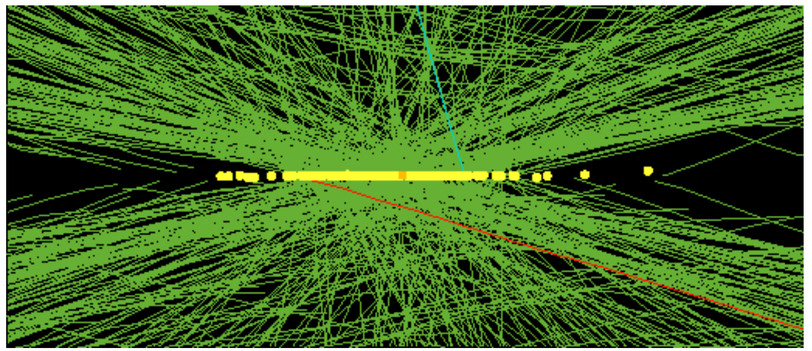


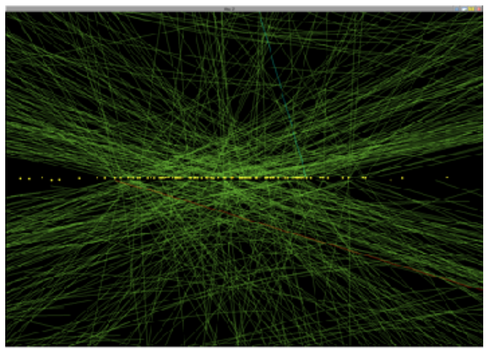
Experimental challenge - pile-up

- With every hard interaction of protons many other protons in the bunch collide
  - Experiments have to separate hard processes from the rest



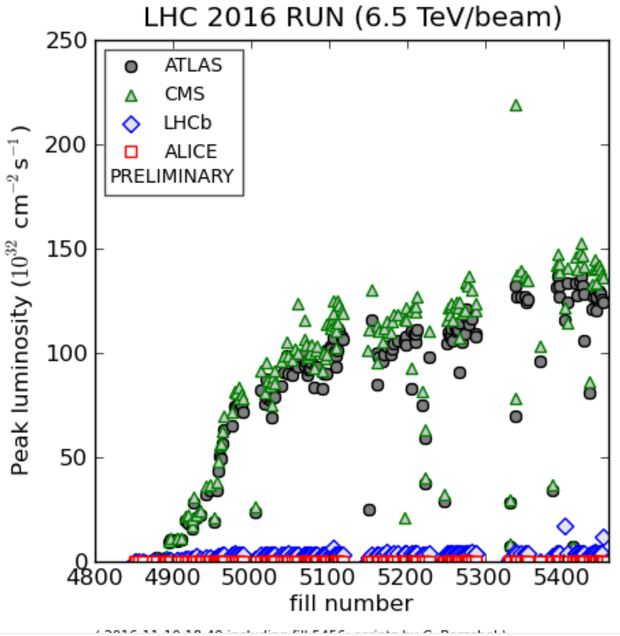


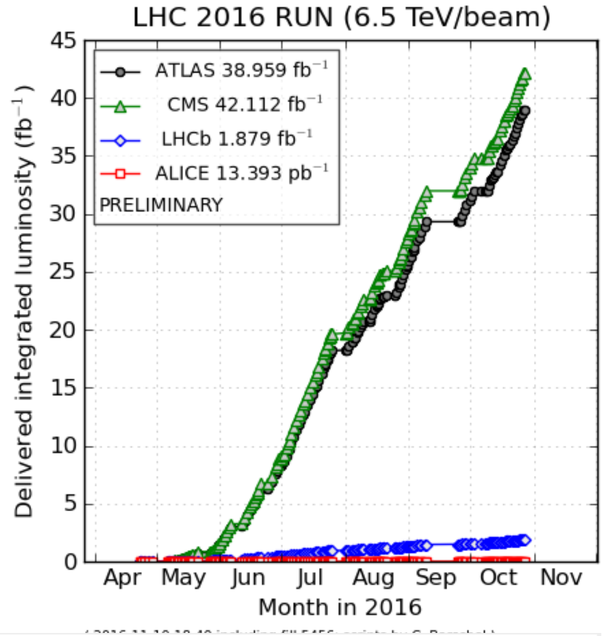


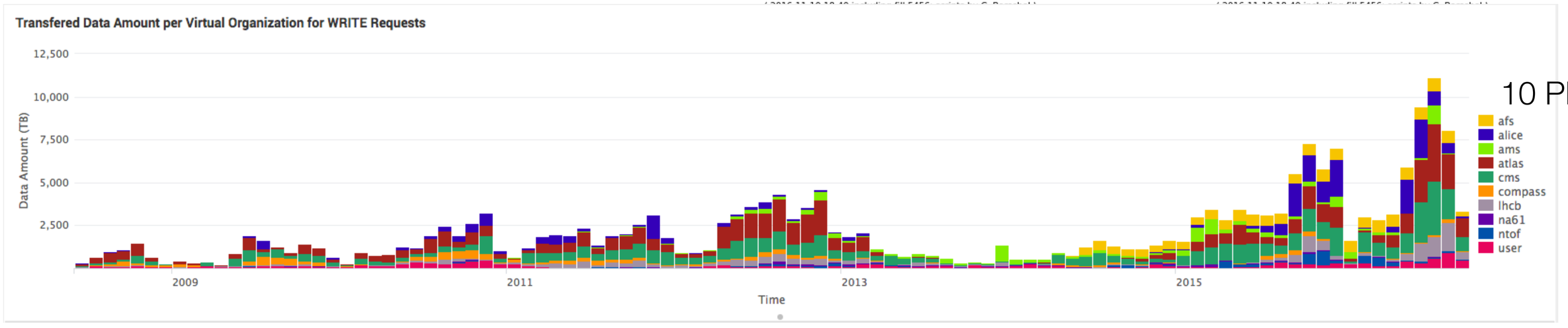


LHC Luminosity 2016 in pp

- Instantaneous (peak) luminosity drives pile-up
- Availability leads to increased computing and data transfer rates
  - >10 PB/month

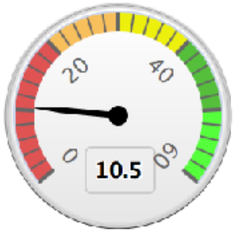




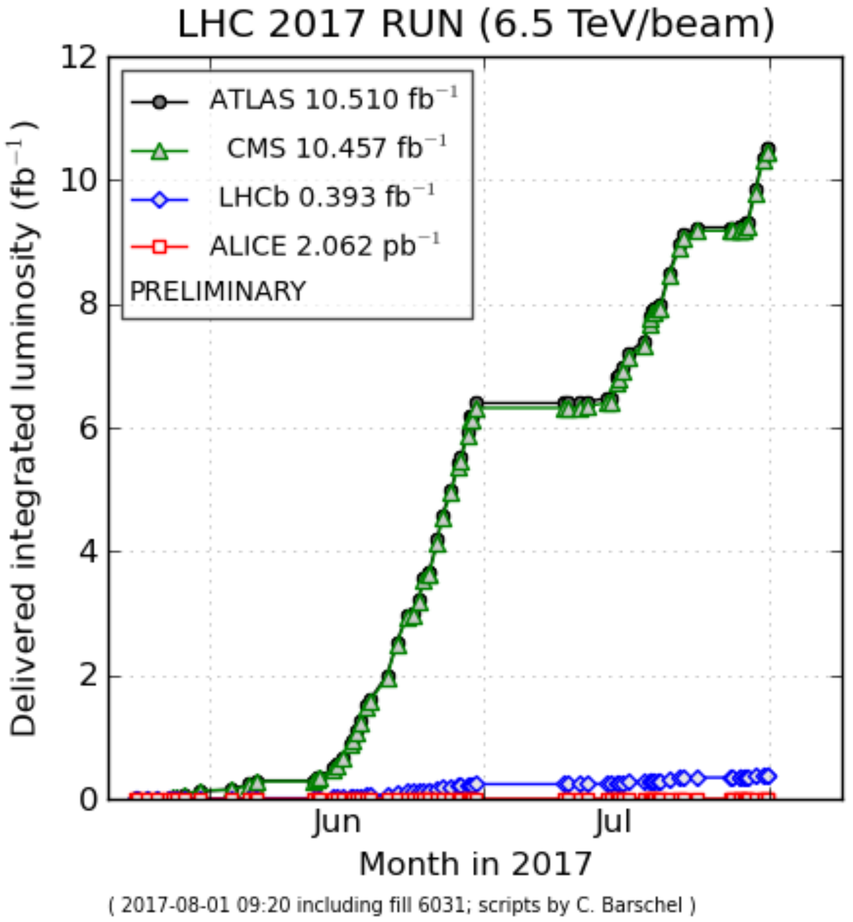


10 PB/m

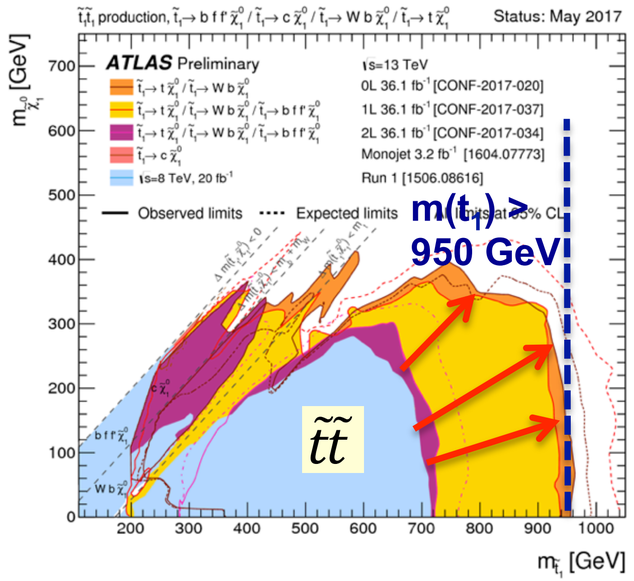
LHC Run 2017 in full swing

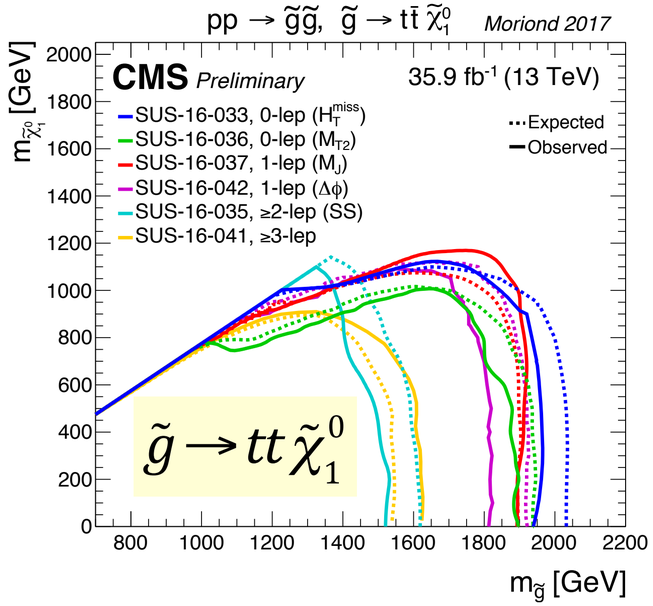


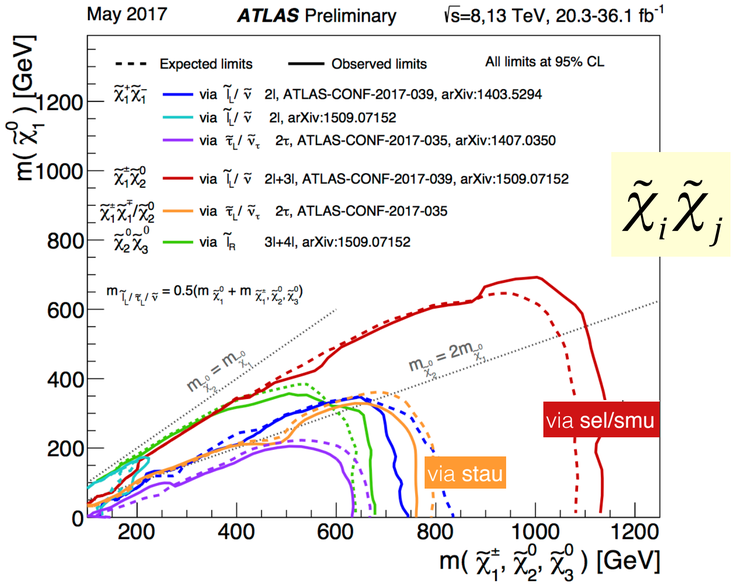
- LHC resumed full operation after extended winter stop which saw replacement of
  - SPS dump (vacuum leak)
  - *sick* LHC dipole in sector 12
- but observe sudden background burst near quadrupole 16L2 leading to occasional dumps
- Experiments carried out their upgrades
  - CMS pixel detector, etc.

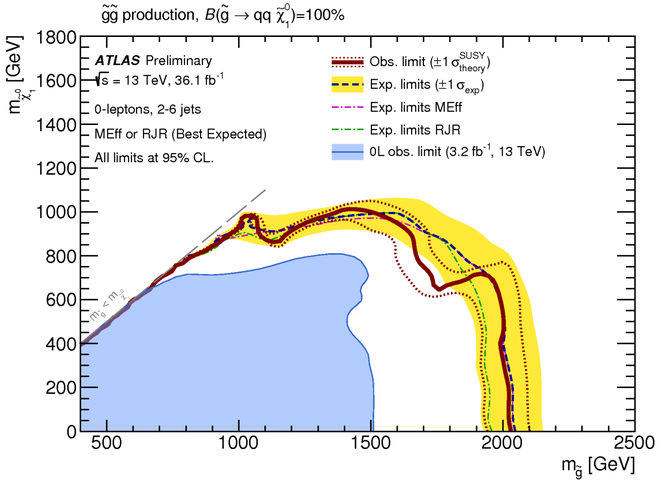


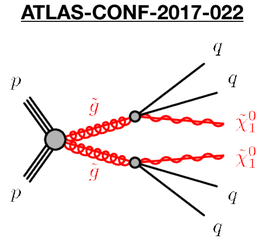
Extending mass reach – example searches for Supersymmetry







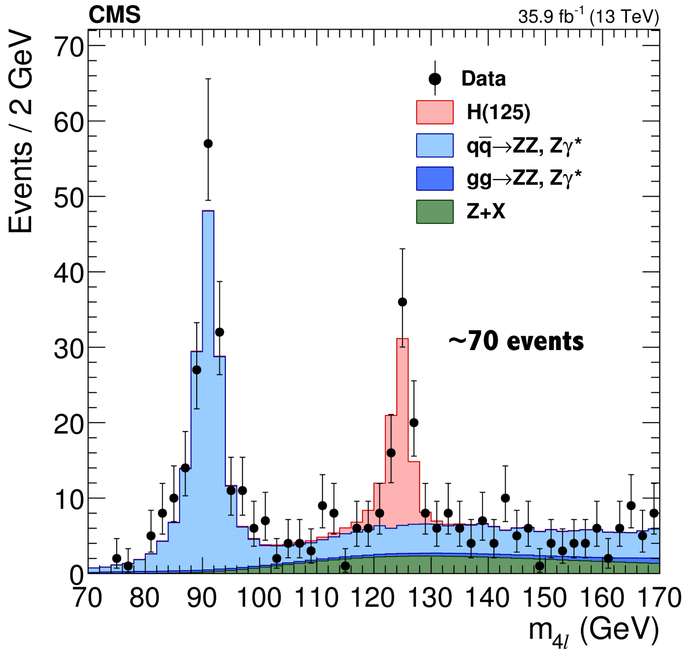




reaching well into TeV region

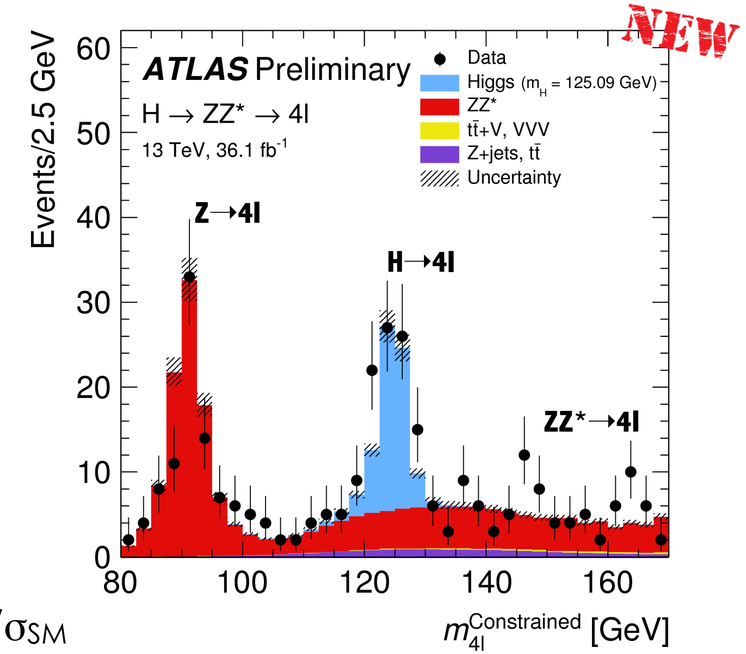
H → 4 ℓ and combination with H → γγ

CMS arXiv:1706.09936 Submitted to JHEP



$$\mu = 1.05^{+0.15}_{-0.14}(\text{stat})^{+0.11}_{-0.09}(\text{syst})$$

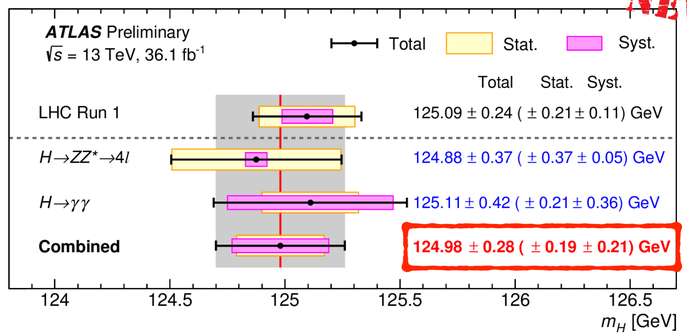
ATLAS-CONF-2017-043



$$\mu = 1.28^{+0.18}_{-0.17}(\text{stat})^{+0.08}_{-0.06}(\text{exp})^{+0.08}_{-0.06}(\text{theo})$$

$\mu = \sigma/\sigma_{SM}$

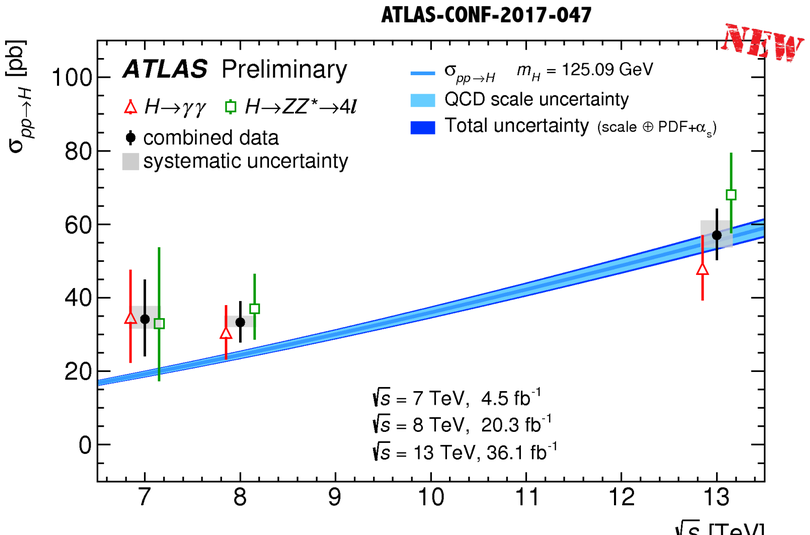
ATLAS-CONF-2017-046



CMS arXiv:1706.09936

$$m_H = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst}) \text{ GeV}$$

ATLAS-CONF-2017-047



H → fermions

Using

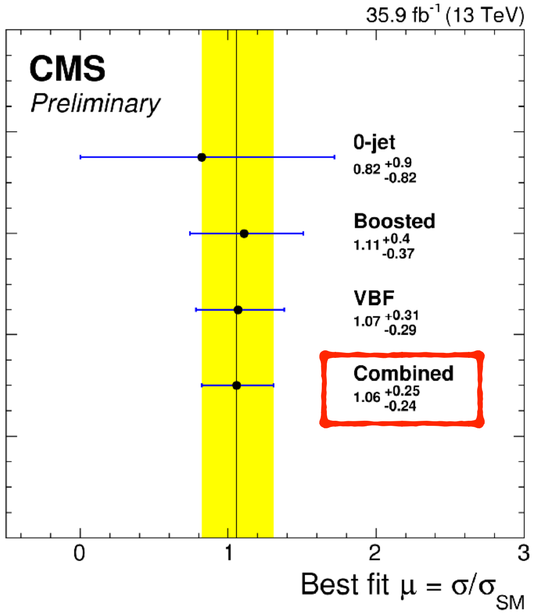
$\tau_h\tau_h$

$e\,\tau_h$

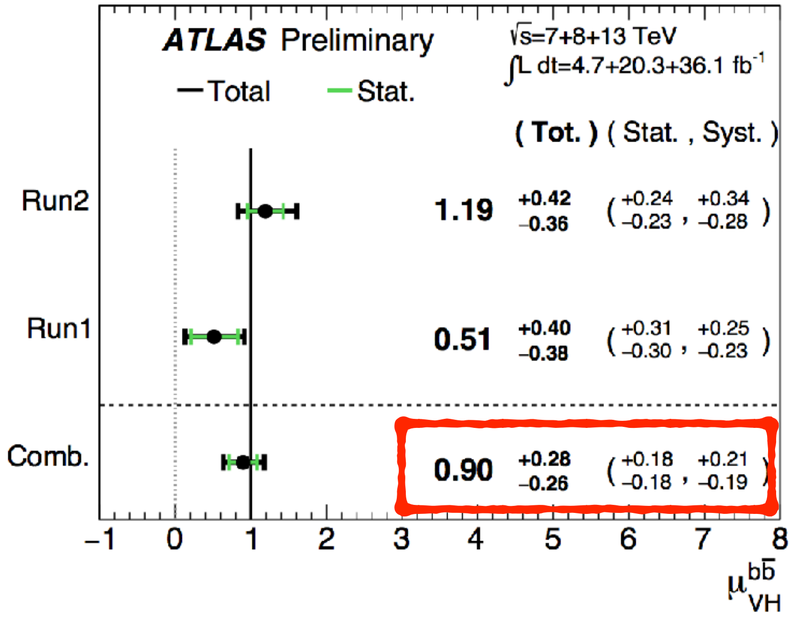
$\mu\,\tau_h$

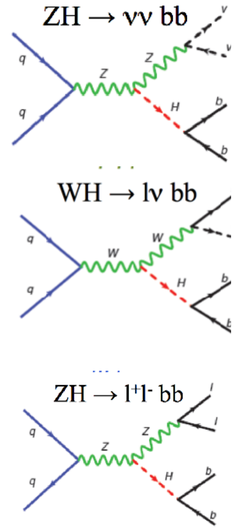
$e\mu$

$H \to \tau\tau$



$H \to b\bar{b}$





4.9 σ from run 2 3.5 σ

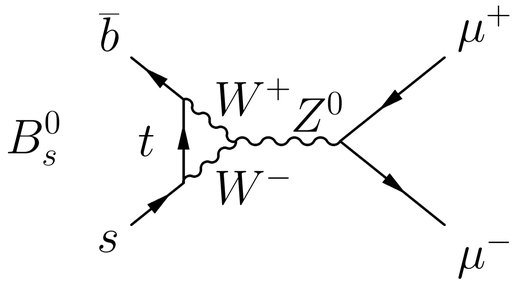
$B^0 \rightarrow \mu\mu$

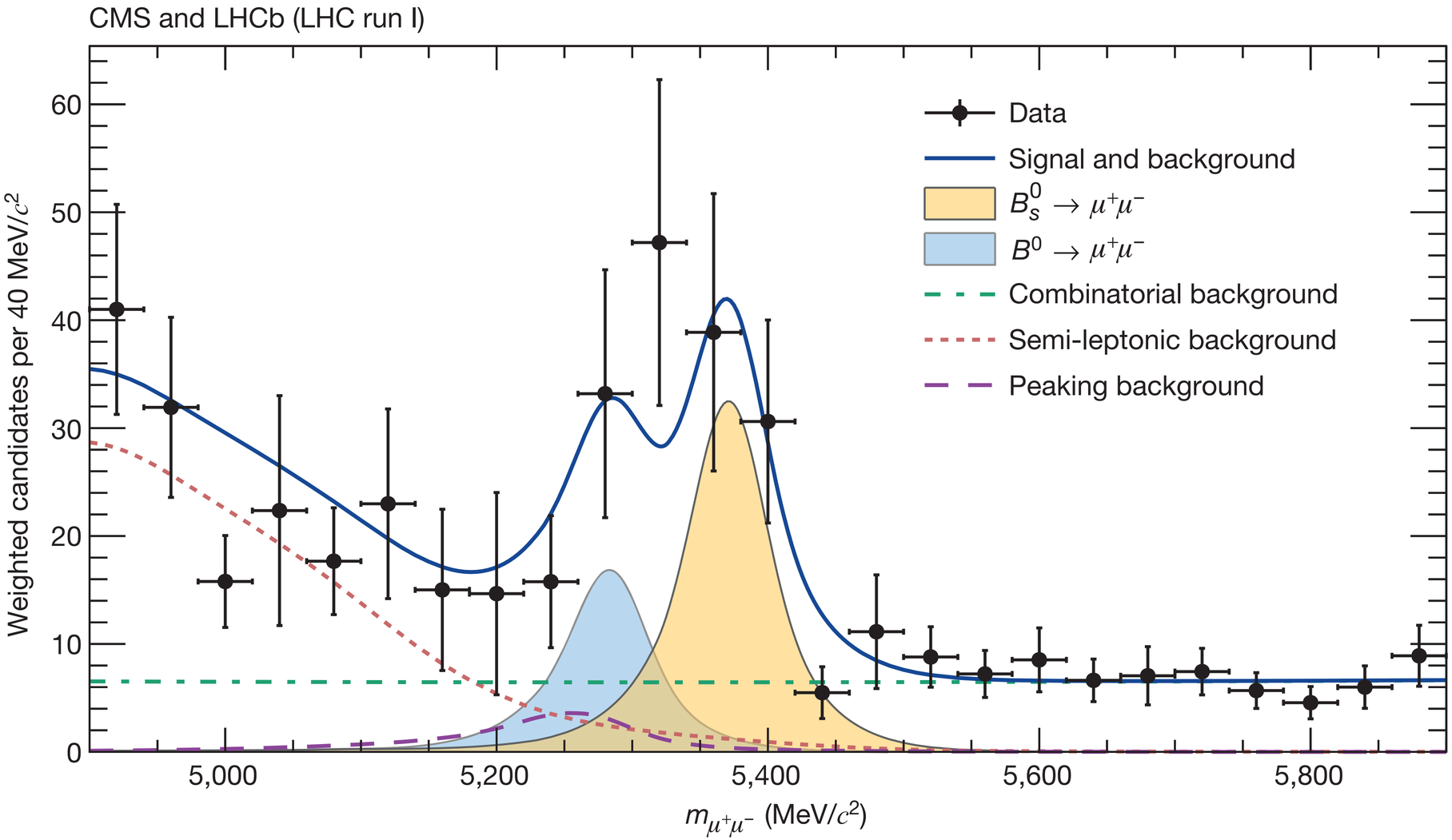
LETTER

Observation of the rare $B_s^0 \rightarrow \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

OPEN doi:10.1038/nature14474

Extremely rare decay in Standard Model



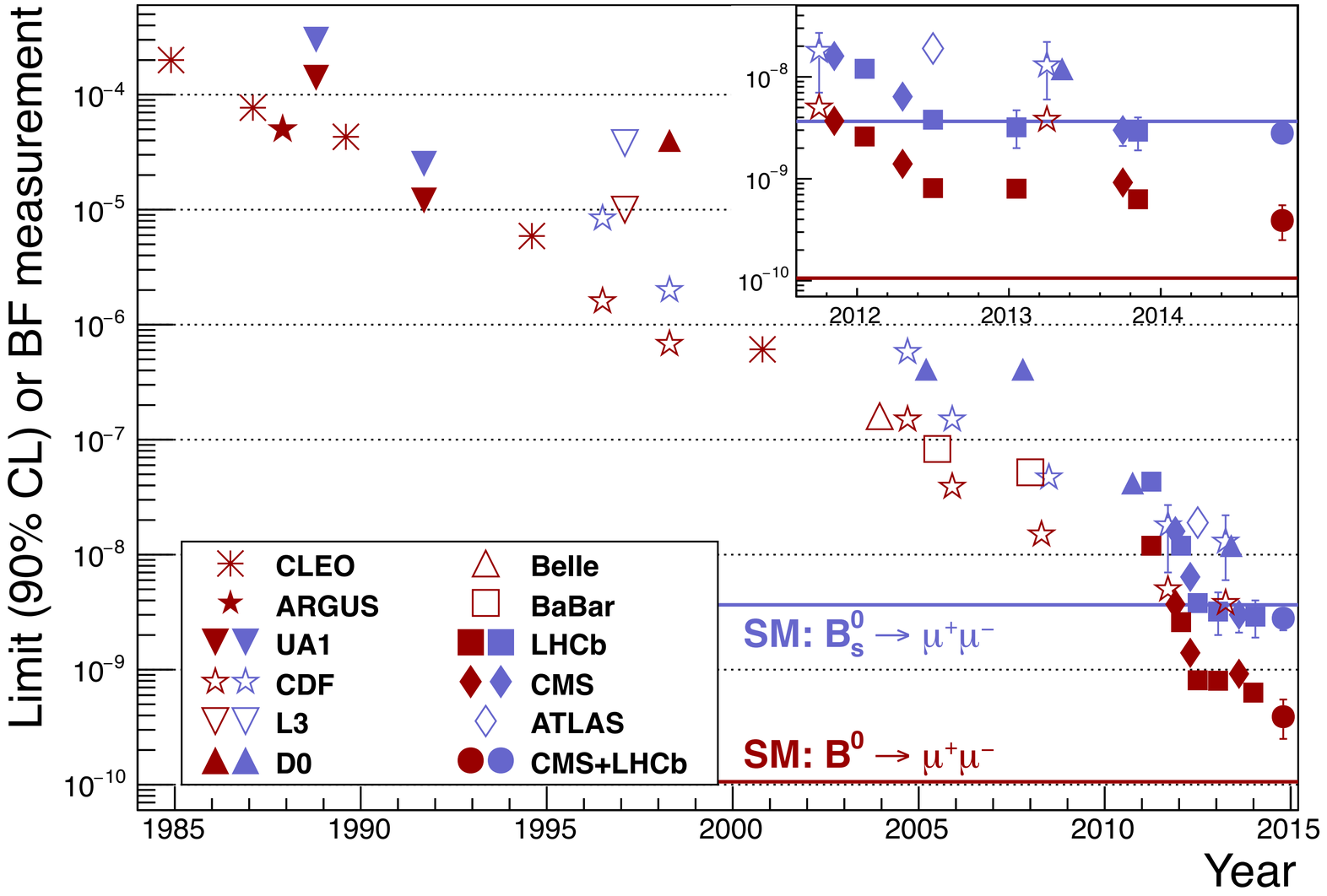


From limit to measurement for $B^0 \rightarrow \mu\mu$

The rare decay was known to be particularly sensitive for new physics.

25 years of experimental research to reach SM sensitivity.

Compatible with SM – new physics not hiding here?



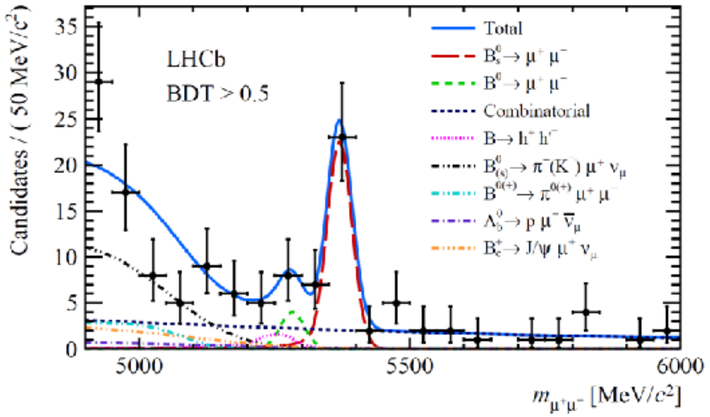
Measurement of BR($B_s \to \mu\mu$) and search for $B_d \to \mu\mu$

Recent result from LHCb alone

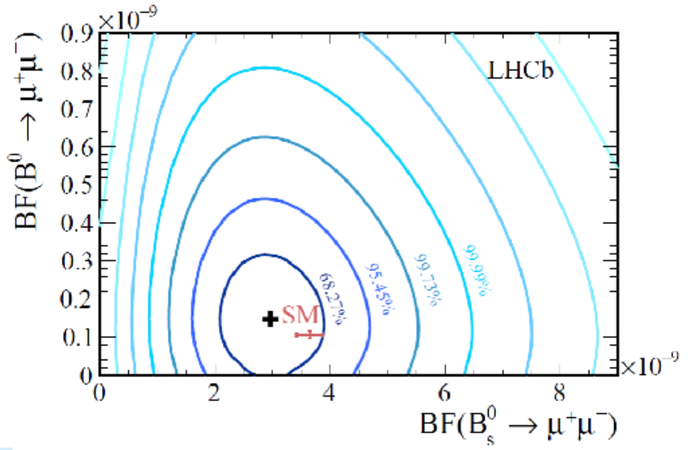
- Re-analyse Run 1 data with improved selection (background halved) and add 1.4 fb^{-1} of Run 2 data

- First single-experiment observation of $B_s \to \mu\mu$ mode; measurement of BR has same precision as previous Run 1 LHCb-CMS combined analysis [Nature 522 (2015) 68].

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$



$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \quad @\,95\,\%\ \text{C.L.}$$



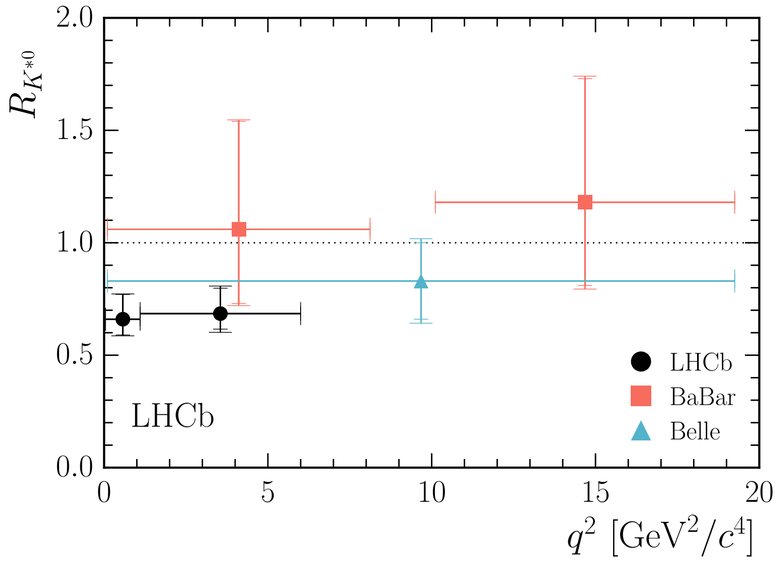
Measurement of R_{K^*}

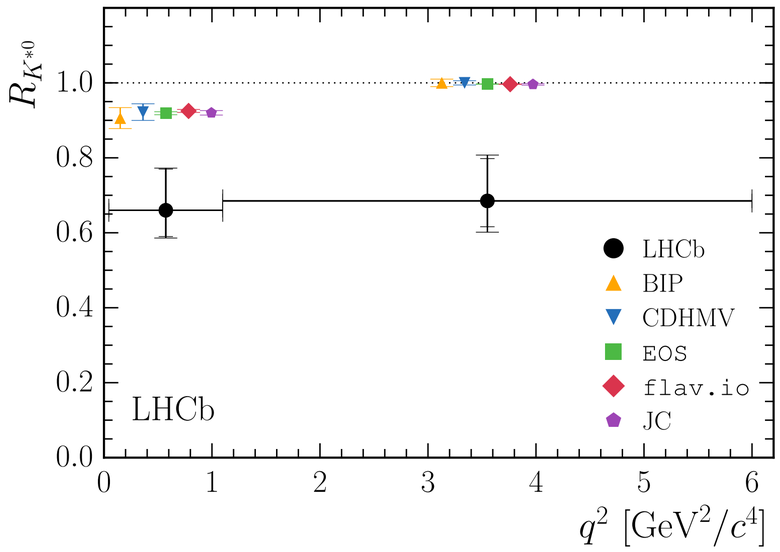
Expect μμ and ee-branchings to be the same – apart from well understood mass contributions

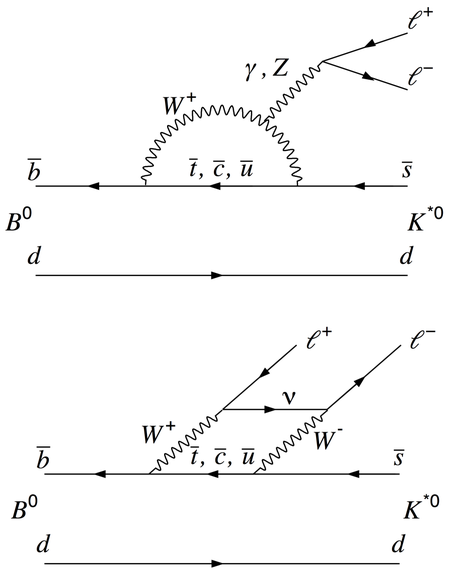
LHCb-Paper-2017-013

So far a ~2.5 σ effect

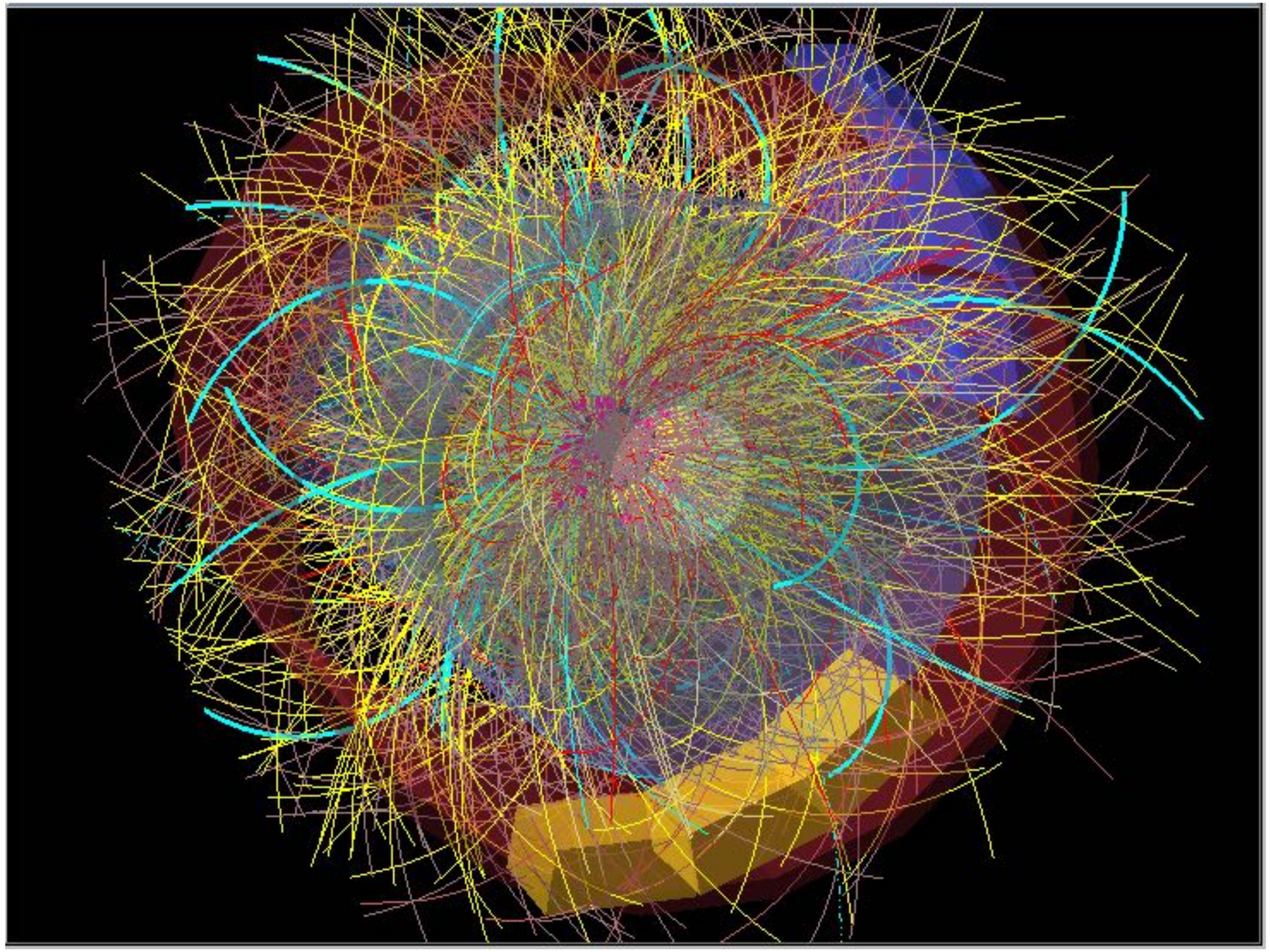
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$







Heavy Ion Physics



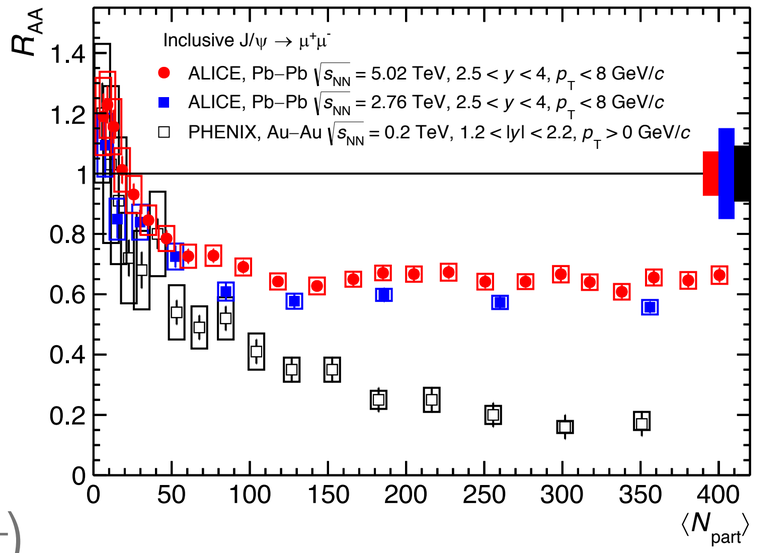
Pb-Pb: J/ψ suppression at 5 TeV

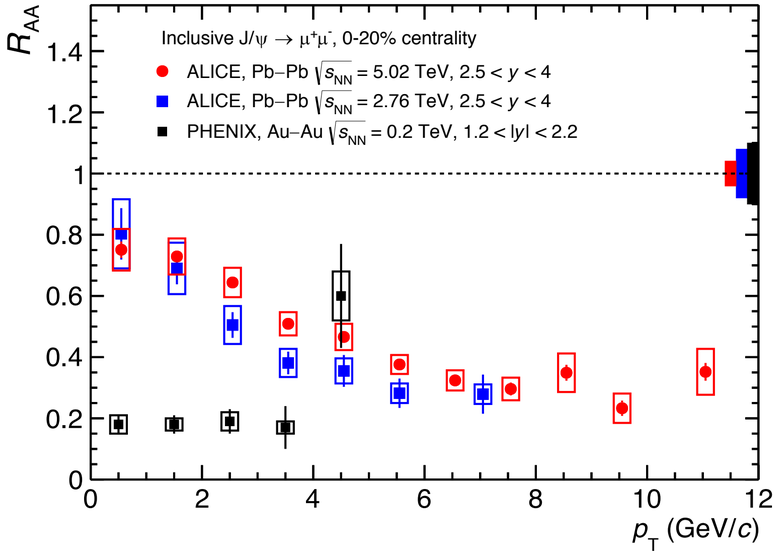
- nuclear modification factor R_{AA}:

$$R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin} \rangle N(J/\psi)_{pp}}$$

- very different behaviour between LHC and RHIC (vs both centrality and p_T)

- most straightforward explanation: c-cbar recombination at LHC



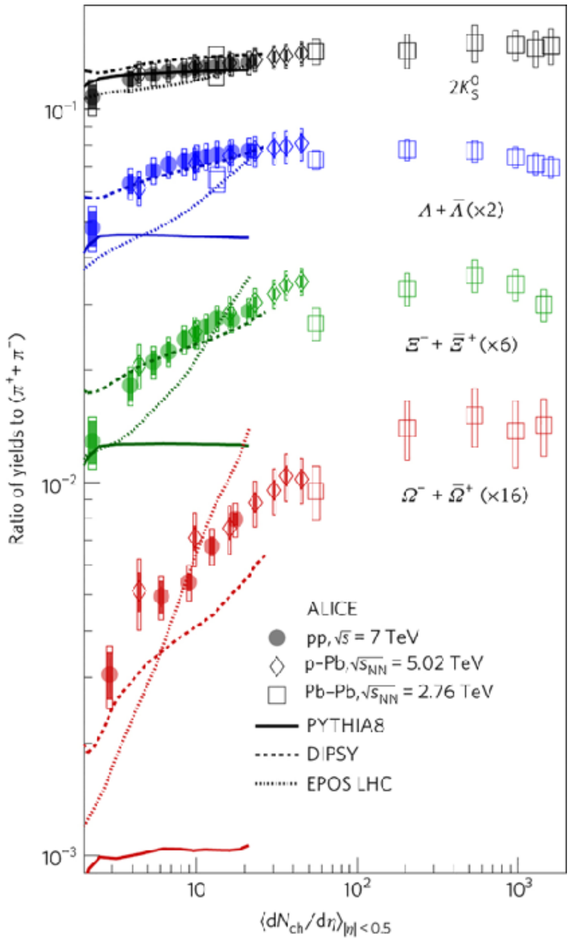


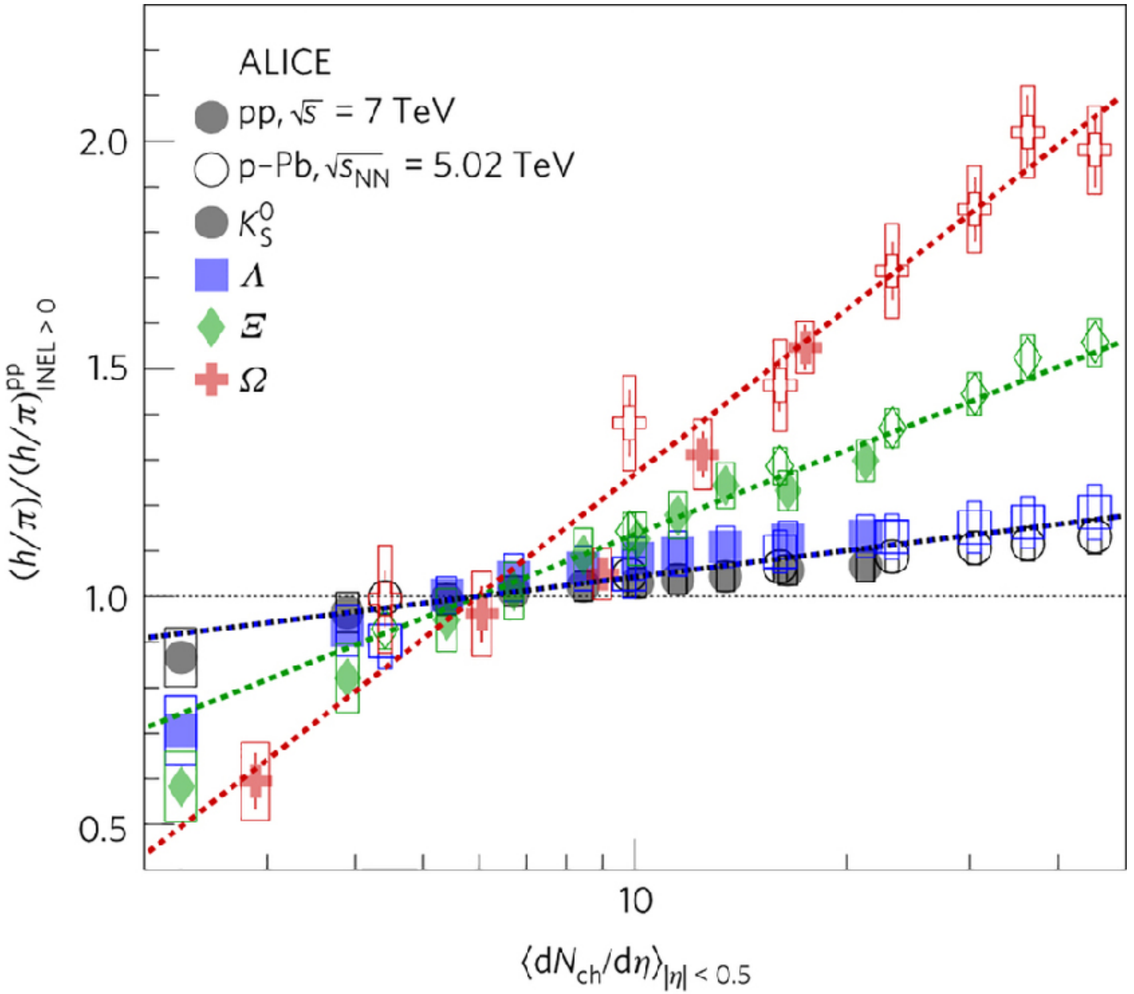
New and precise 5 TeV data support even further increase

Strangeness production in high-energy pp

Strangeness increases in high-multiplicity pp-collisions

Evidence for Quark-Gluon plasma in pp collisions





High Luminosity LHC

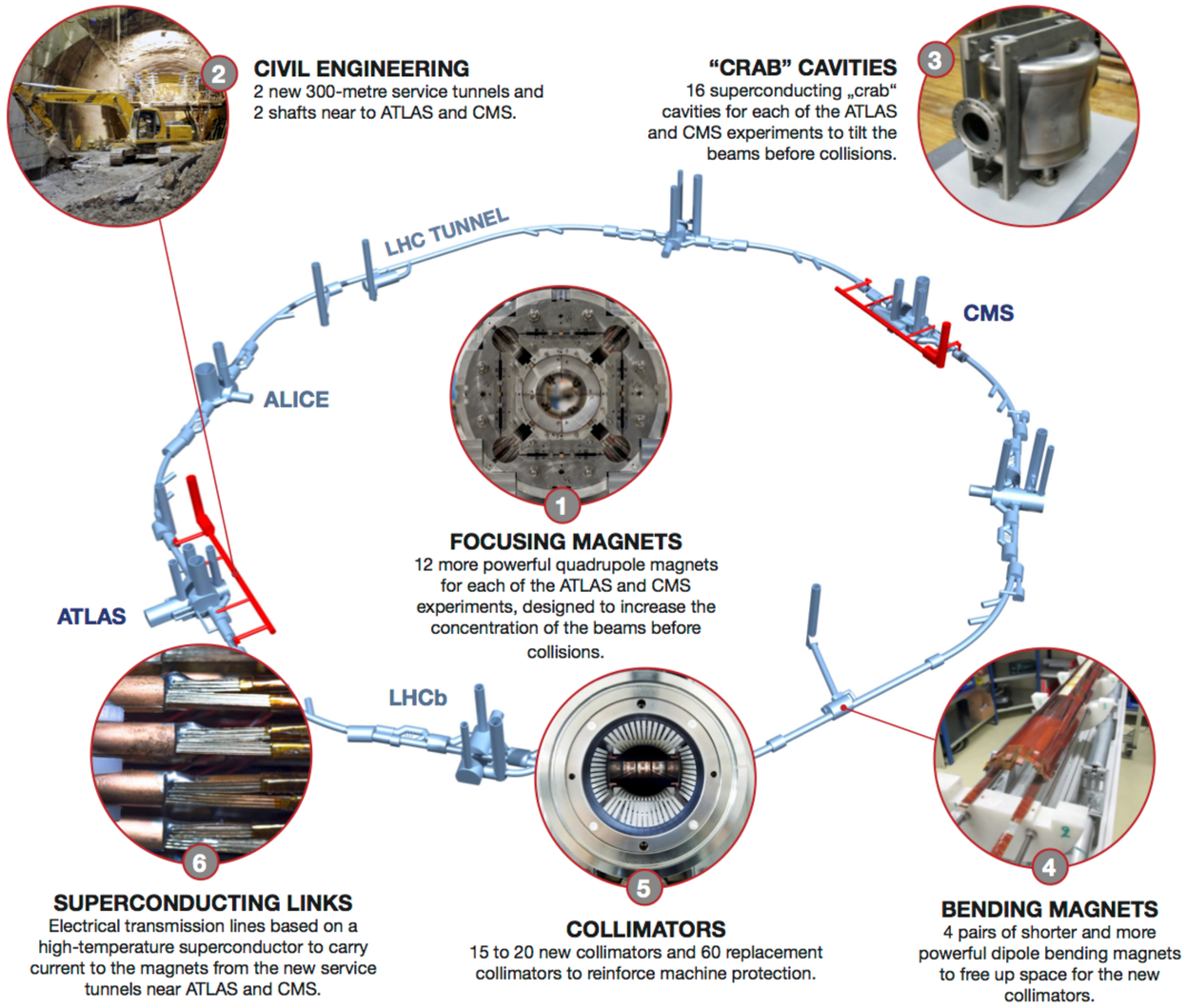
High-Luminosity LHC approved by Council in 2016

High-Luminosity (HL-LHC)

- $5x10^{34}$ $cm^{-2}s^{-1}$ levelled; i.e. factor 5 over design
  - to yield 3 ab^{-1} by ~2035

requires

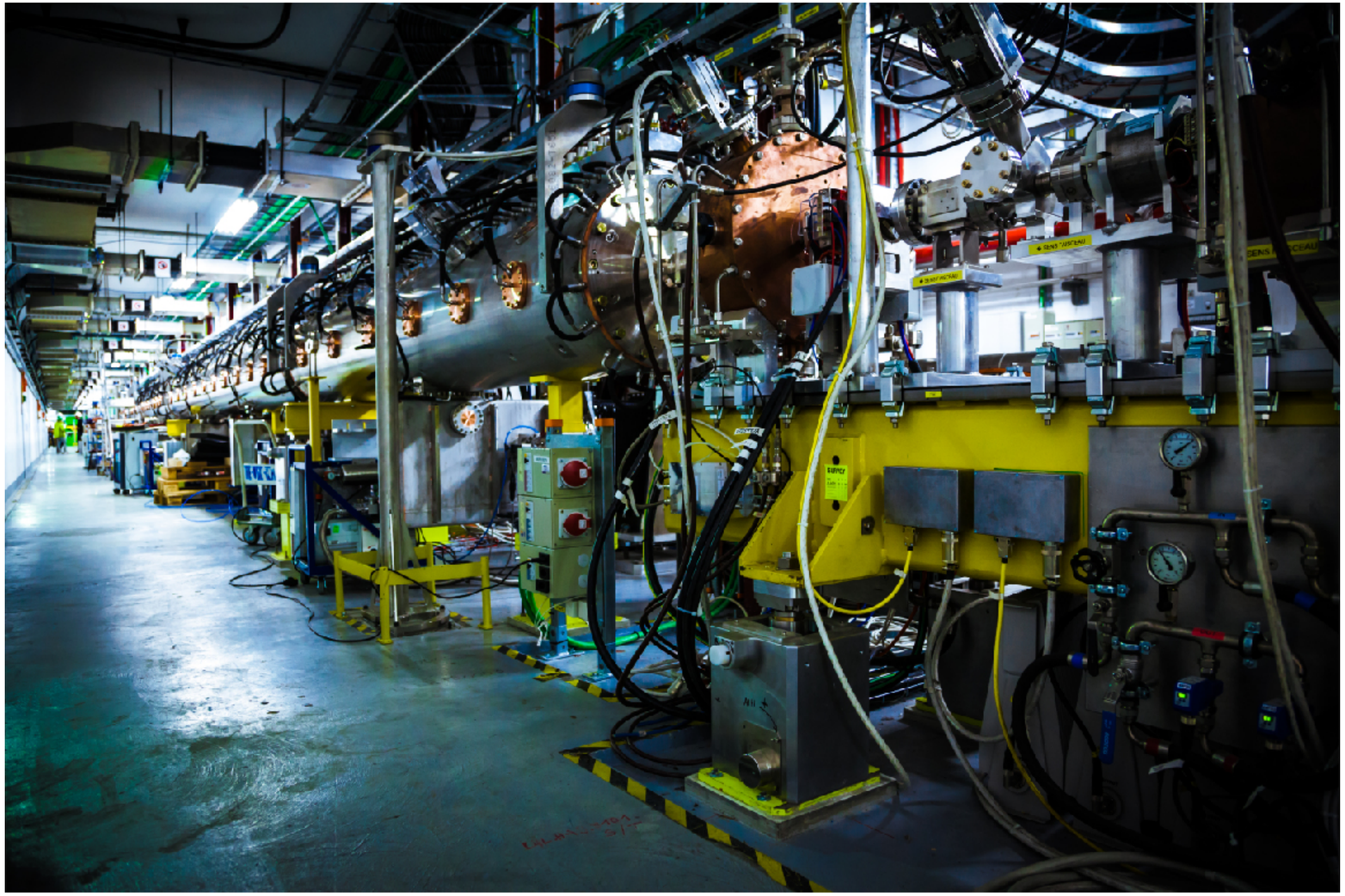
- focussing β^*=15 cm
- crab crossing



LHC-Injector upgrades – Linac 4 taken into operation*

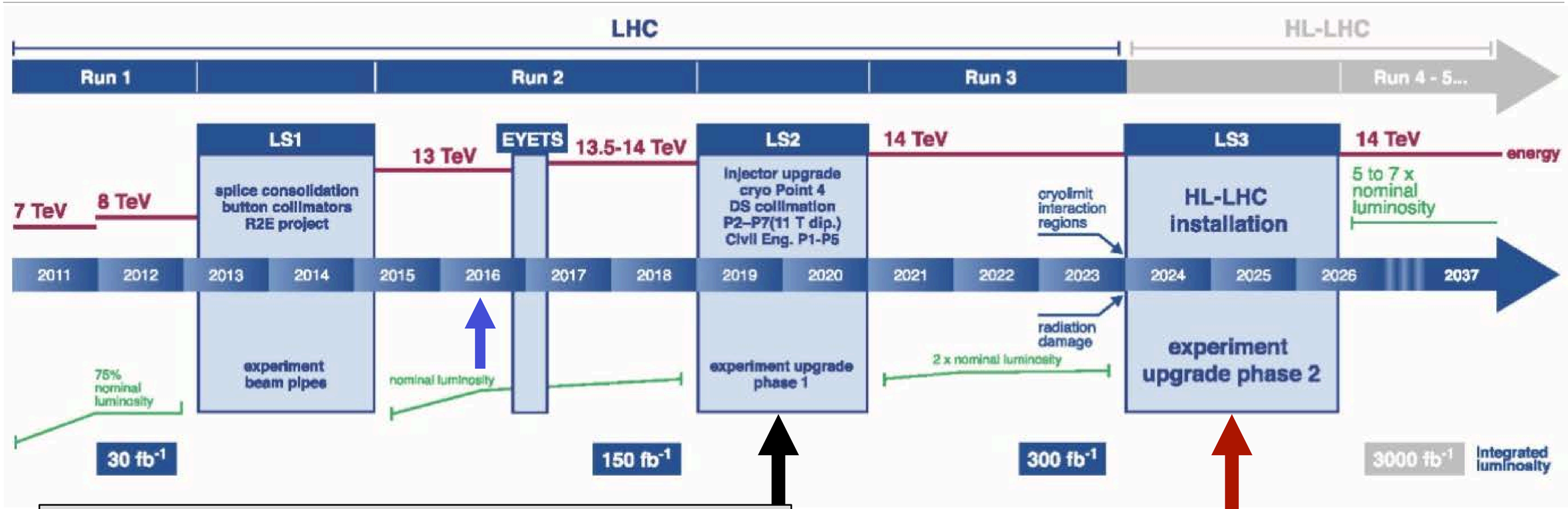
- Commissioning started 2014
- protons have been accelerated to 160 MeV
- using π-mode structures PIMS for high energy acceleration

Inauguration 9.5.2017



*not yet connected to booster

HL-LHC schedule



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

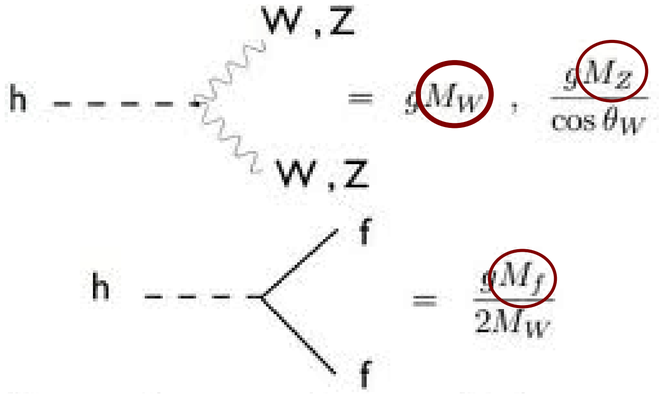
LS3 (2024-2026):

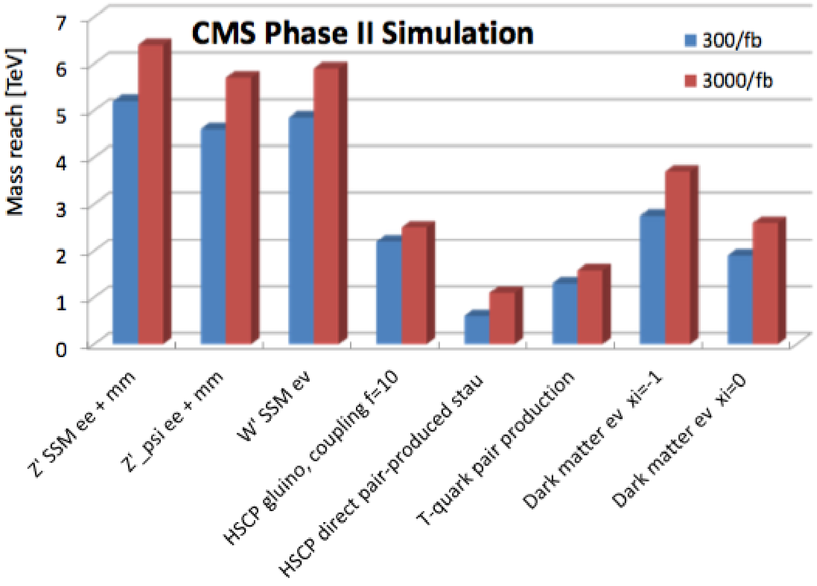
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

A few physics example for HL-LHC

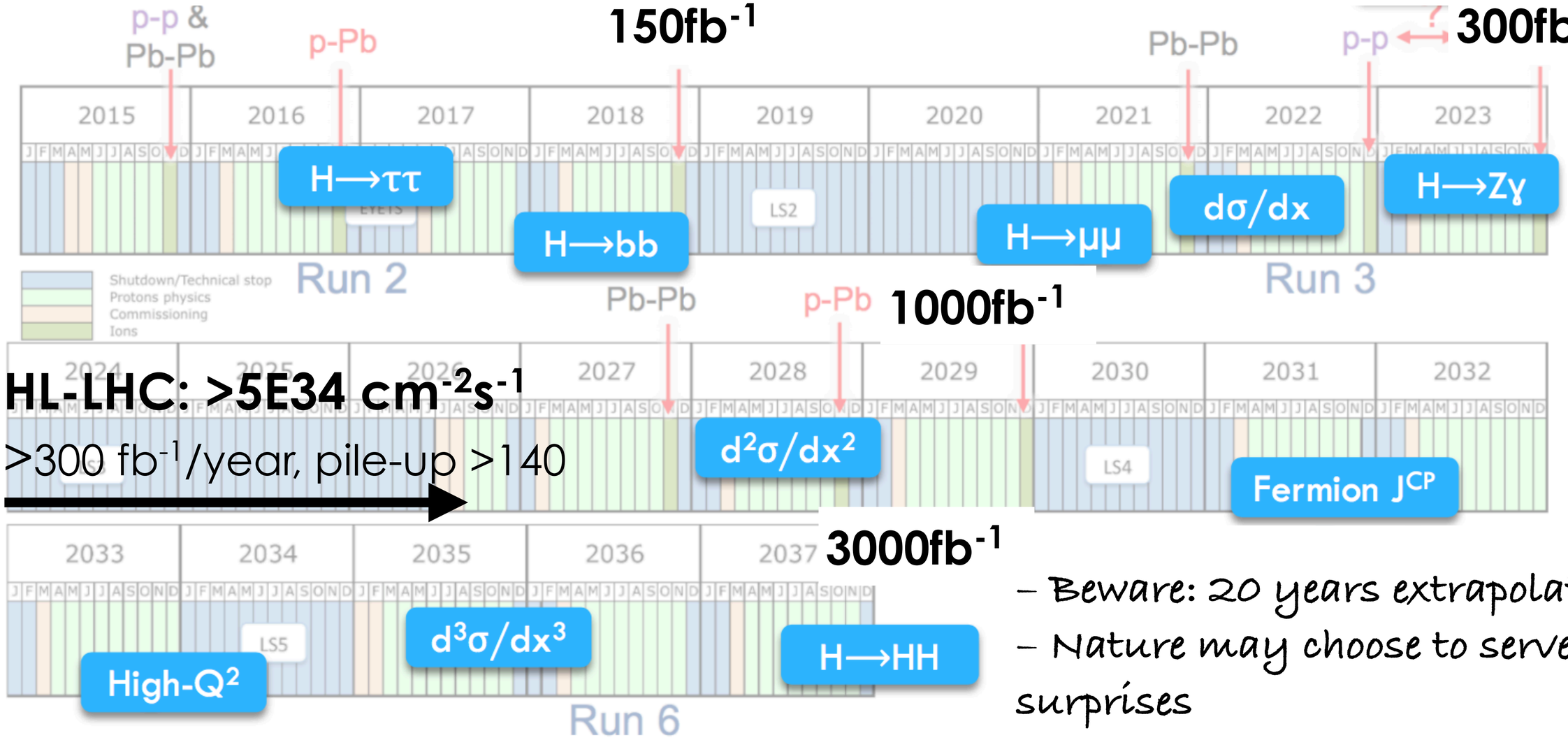
- measurement of Higgs couplings
  - deviations may be at the few %-level
  - access to second generation couplings H→μμ
- 20-30% larger discovery potential (8 TeV)
  - precision measurements





SM Physics Menu on the LHC and HL-LHC Running Schedule

Credits: A. David @ GRC 2017



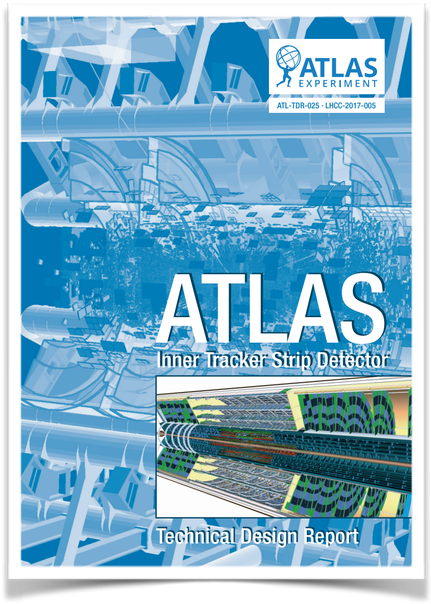
- Beware: 20 years extrapolation
- Nature may choose to serve surprises

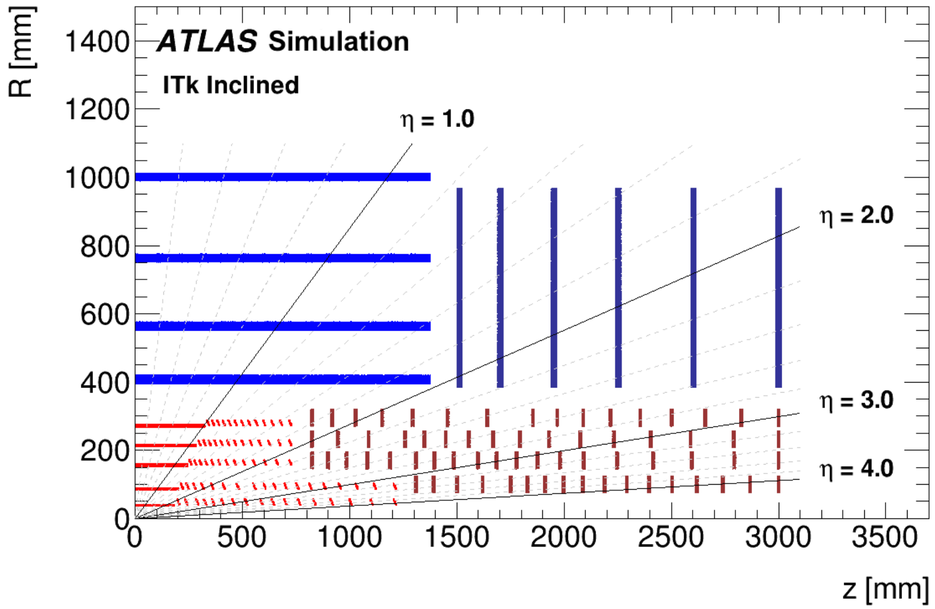
Phase II Detector upgrades

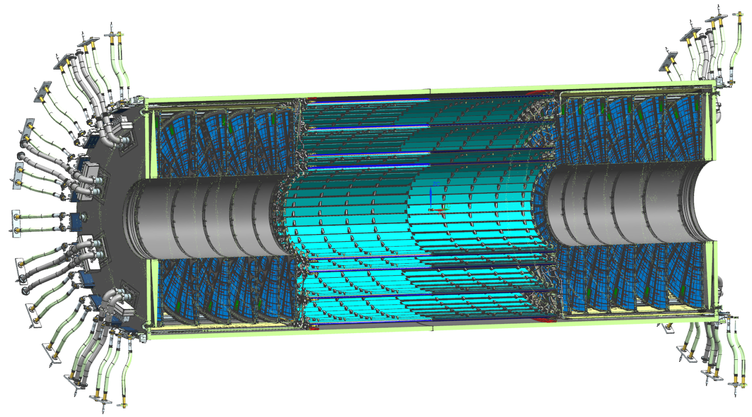
- replace radiation-damaged components
- enable detectors to withstand the rates at phase I performance

ATLAS ITk strips TDR (Phase II Upgrade)

- Settled on 5 pixel + 4 strips system
- Only the strips are evaluated in TDR – although status of pixel mentioned
- The pixel TDR will follow at the end of 2017
- Large document (>500 pages)







Planned deluge of Technical Design Reports (TDRs)

Experiment	System	Date	CORE MCHF	SOURCE
ATLAS	ITkStrip	Dec-16	61	TDR ITkStrip
ATLAS	Muon	Jun-17	34	SD
ATLAS	LAr	Sep-17	36	SD - sFCal
ATLAS	Tile	Sep-17	9	SD
ATLAS	TDAQ	Dec-17	43	SD
ATLAS	ITkPixel	Dec-17	59	SD
CMS	Tracker	Jul-17	112	SD
CMS	Barrel Cal	Sep-17	11	SD
CMS	Muon	Sep-17	25	SD
CMS	Endcap Cal	Nov-17	64	SD
CMS	Trigger DAQ/HLT	>2019	24	SD

SD=
Scoping Documents

ATLAS
Letter of Intent + Scoping Document
CERN-LHCC-2012-022
CERN-LHCC-2015-020

CMS
Technical Proposal + Scoping Document
CERN-LHCC-2015-010
CERN-LHCC-2015-019

Timeline

TDR	COST	Jun-17	Jul-17	Aug-17	**Sep-17**	Oct-17	**Nov-17**	Dec-17	Jan-18	**Feb-18**	Mar-18	Apr-18
						RRB	Special		Special		Special	RRB
ATLAS Strip ITK	61	RB										
ATLAS Muon	34		Draft		UCGP	LHCCR	Pub	UCGR		RB		
ATLAS LAr	36					Draft		UCGP	LHCCR	Pub	UCGR	RB
ATLAS pixel ITk	59									Draft	UCGP	LHCCR Pub UCGR RB
ATLAS Tile	9					Draft		UCGP	LHCCR	Pub	UCGR	RB
ATLAS TDAQ	43									Draft	UCGP	LHCCR Pub UCGR RB
CMS Tracker	112	Preview	Draft		UCGP	LHCCR	Pub	UCGR		RB		
CMS Barrel Cal	11					Draft		UCGP	LHCCR	Pub	UCGR	RB
CMS End Cap Cal	64								Draft		UCGP	LHCCR Pub UCGR RB
CMS Muon	25					Draft		UCGP	LHCCR	Pub	UCGR	RB
CMS TDAQ	24					IntDoc						

codes

LHCC review	LHCCR	Preview TDR	Preview
UCG Review	UCGR	Final Draft TDR	Draft
RB Submission	RB	Public TDR	Pub
		UCG Package	UCGP

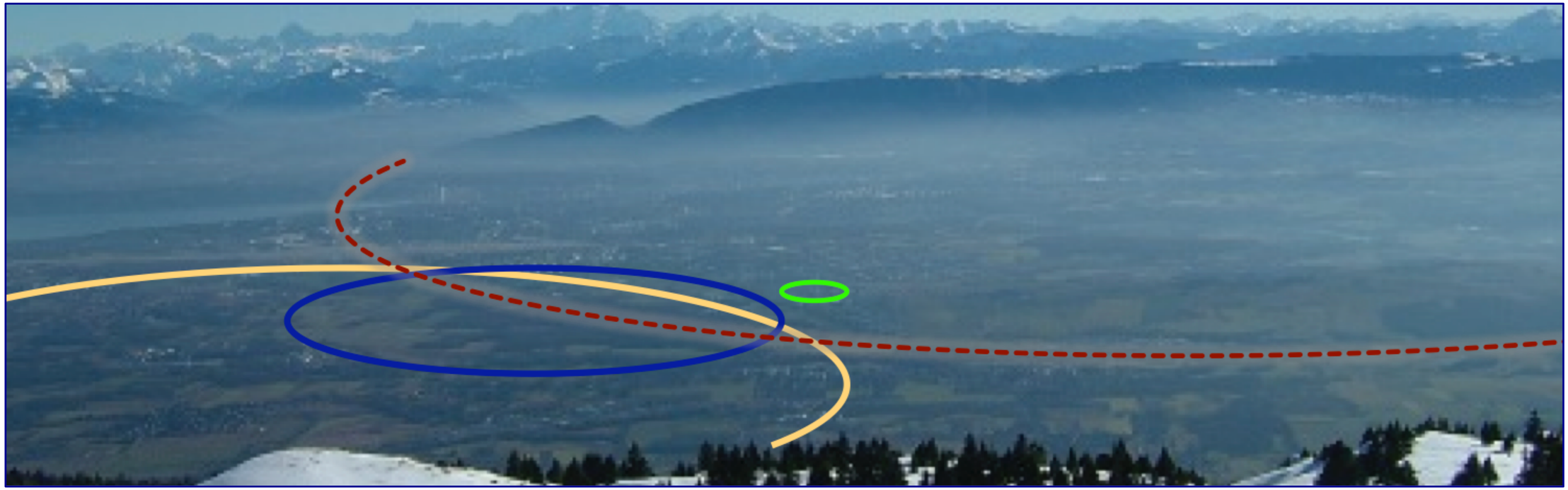
Indication of physics, technical and cost scrutiny of the upgrade process of the experiments

Highest energy hadron colliders

From European Strategy of Particle Physics

CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

Future Circular Collider FCC



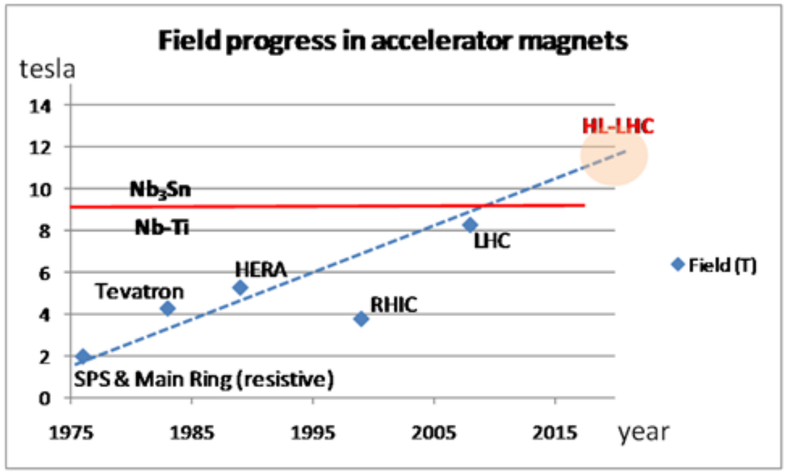
- Study for A 100 km ring providing collisions at 100 TeV cm
  - employs injector chain of CERN

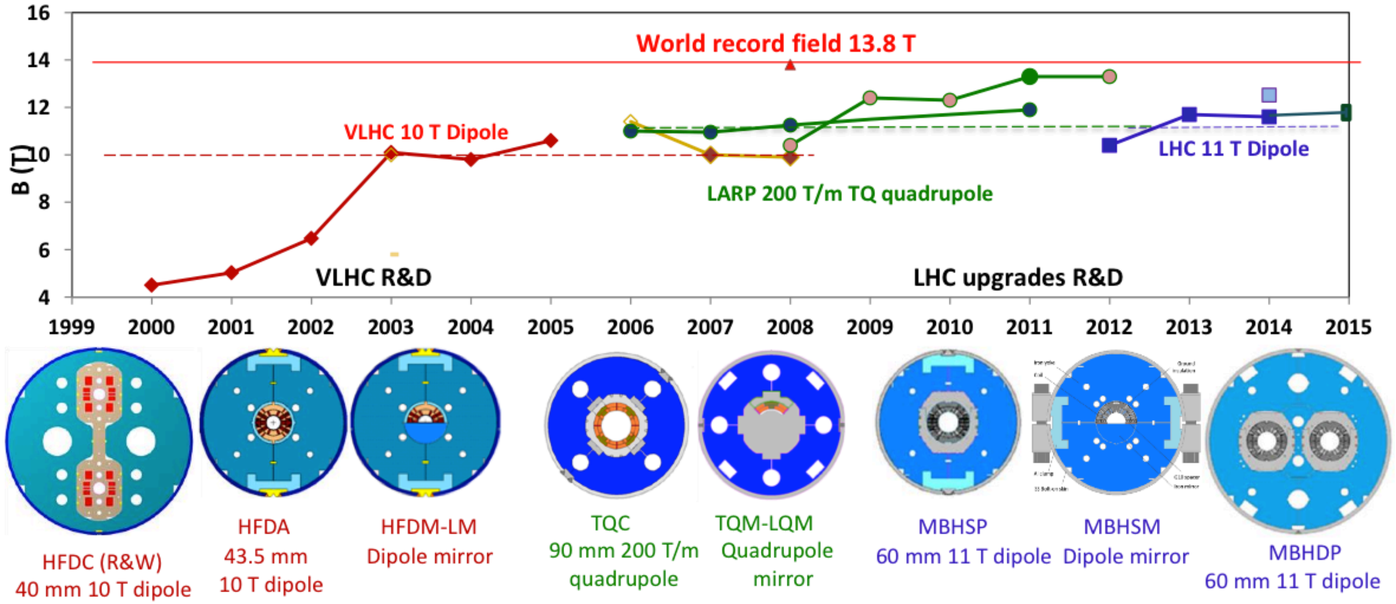
High-field magnets

- Key to high energies
  - FCC and
  - HE-LHC = use of high field magnets in existing LHC ring
- Technology
  - Nb_3Sn allows ~16 T magnets that need to be developed (size, cost, industry…)
    - HL-LHC magnets provide a ~1.2 km test of the technology (11 T magnets)
  - an insert of HTS may increase field to 20 T (requires considerable research)

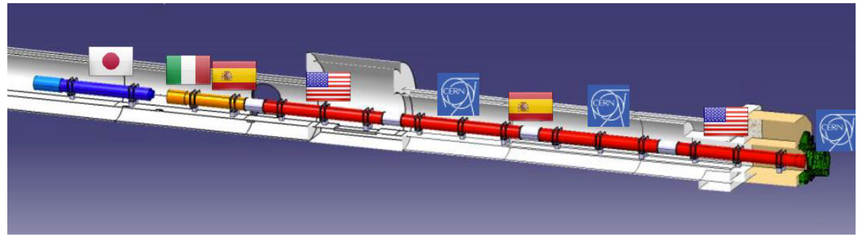
International Collaboration on Magnet Development

- Nb_3Sn magnets: international R&D programme
  - several European countries and US LARP programme and its successor



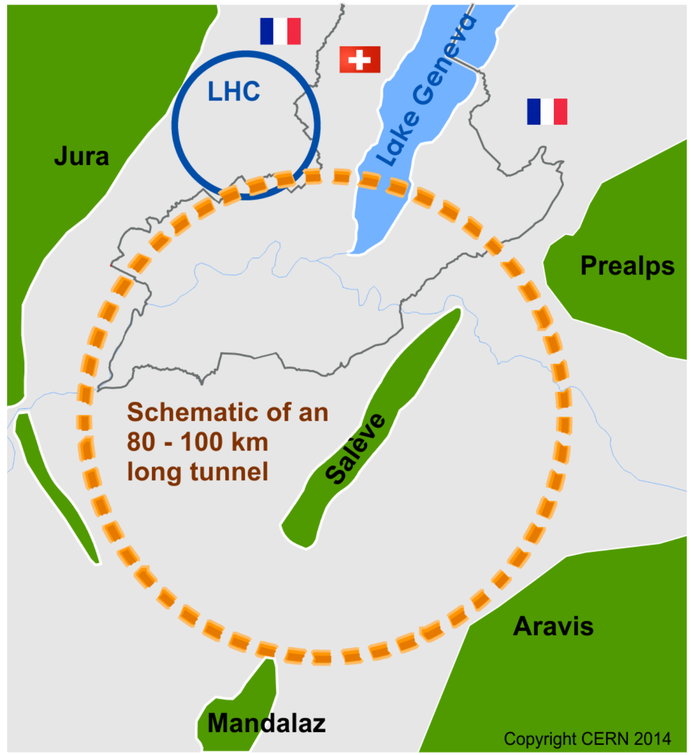


1.2KM of LHC modified



FCC Conceptual Design Report by end 2018

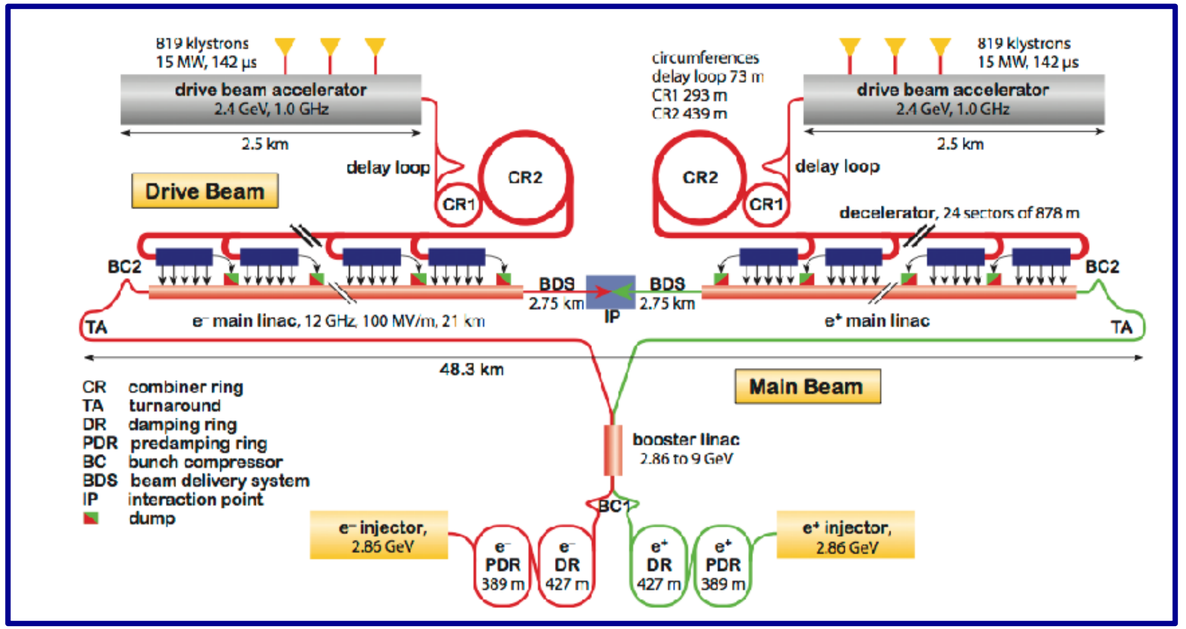
- **pp-Collider (FCC-hh) – sets the boundary conditions**
  - **100 km ring, √s=100 TeV, L~2x10^{35}**
  - **HE-LHC is included (~28 TeV)**
- e^+e^--Collider as a possible first step
  - √s= 90 - 350 GeV,
    L~1.3x10^{34} at high E
- eh-Collider as an option
  - √s=3.5 TeV, L~10^{34}



Highest energy with lepton colliders

Compact Linear Collider CLIC

- e^+e^- collider 1-3 TeV
- currently only option for the TeV region
- 380 GeV study has been completed both for 2-beam and klystrons approach; now explore 250 GeV
- decisive input to next update of European Strategy for Particle Physics



- CDR 2013
- CTF3 has provided key results
  - experimental programme ended 2016
- ready for a demonstrator

e^+e^- collider

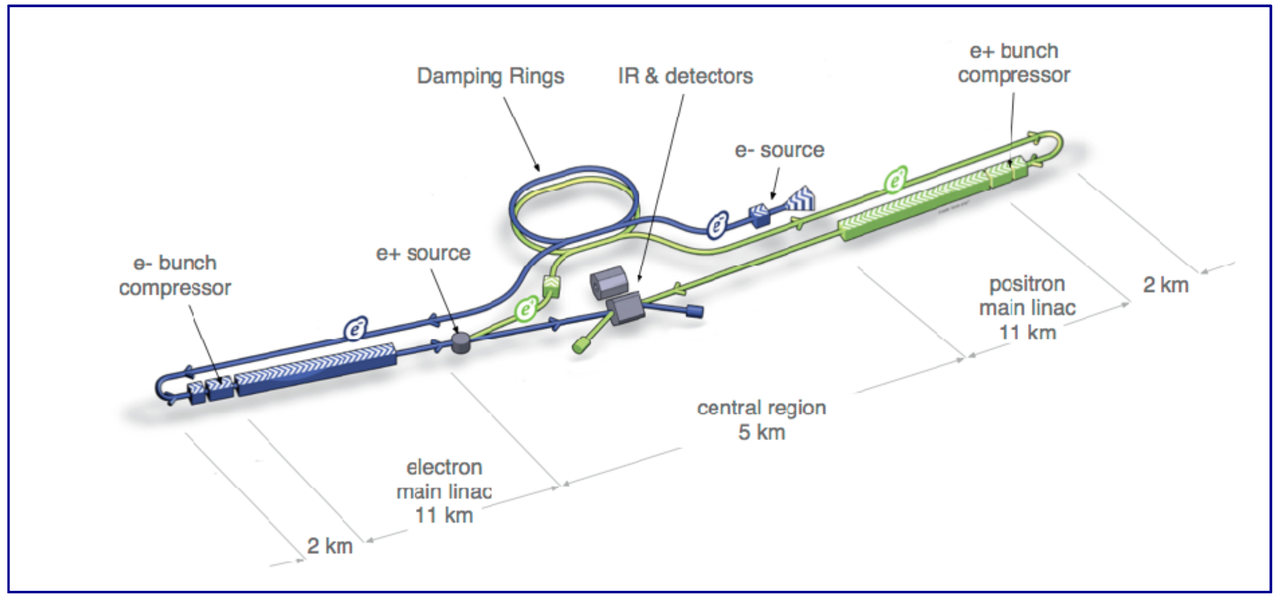
From European Strategy of Particle Physics

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

Europe looks forward to a proposal from Japan to discuss a possible participation.

International Linear Collider ILC

- e^+e^- collider $\sqrt{s}$ = 0.5 TeV (upgradeable to 1 TeV)
  - staged version for $\sqrt{s}$ = 0.25 TeV being promoted
- precision Higgs (and Top) programme and beyond
- Ministry MEXT continues to evaluate the implications of hosting ILC in Japan w.r.t. cost, manpower (skills)



- Project is mature (TDR 2012)
- hosting evaluated by Japanese government
- expect (some) statement by the end of 2018

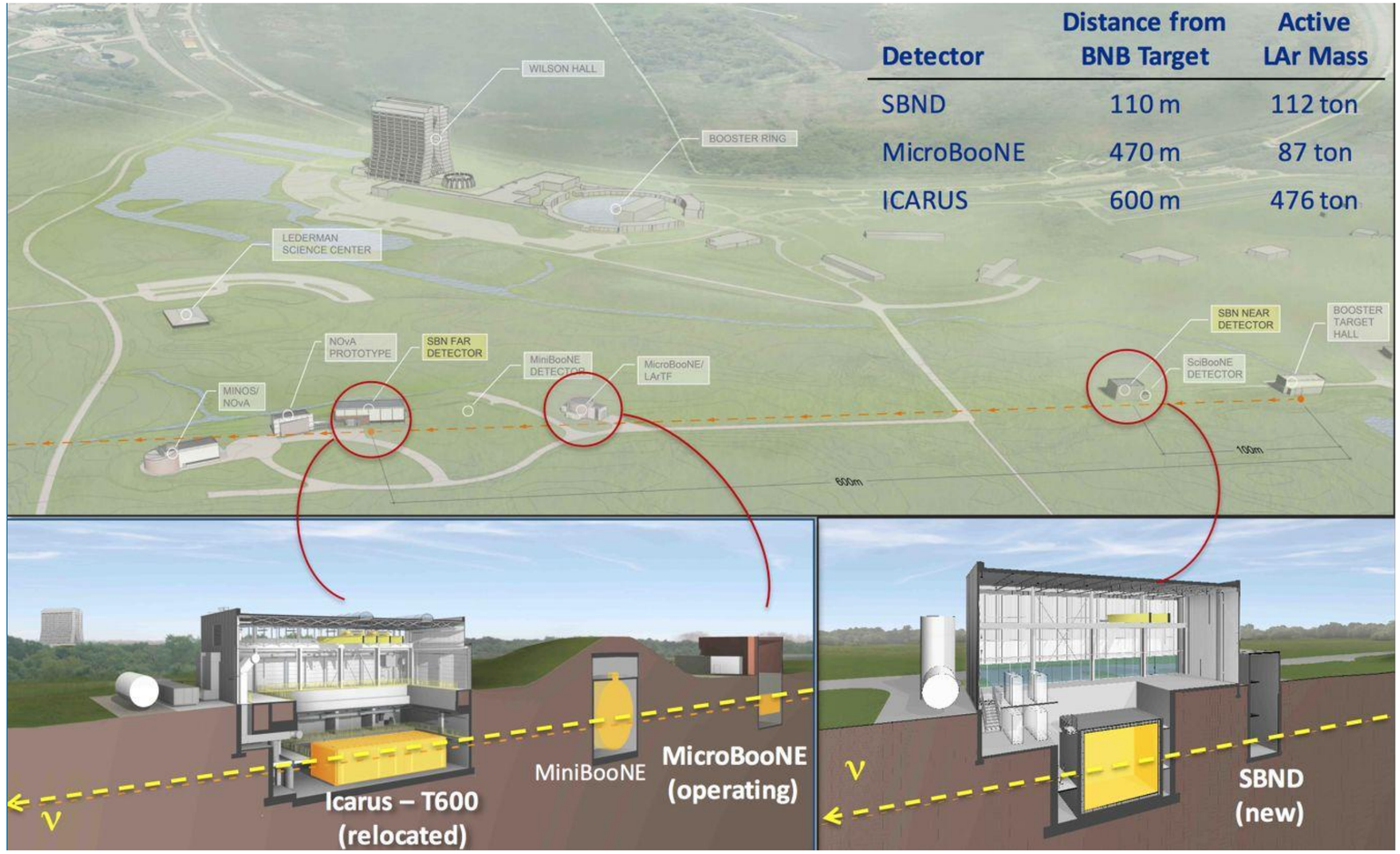
v-physics

From European Strategy of Particle Physics

Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

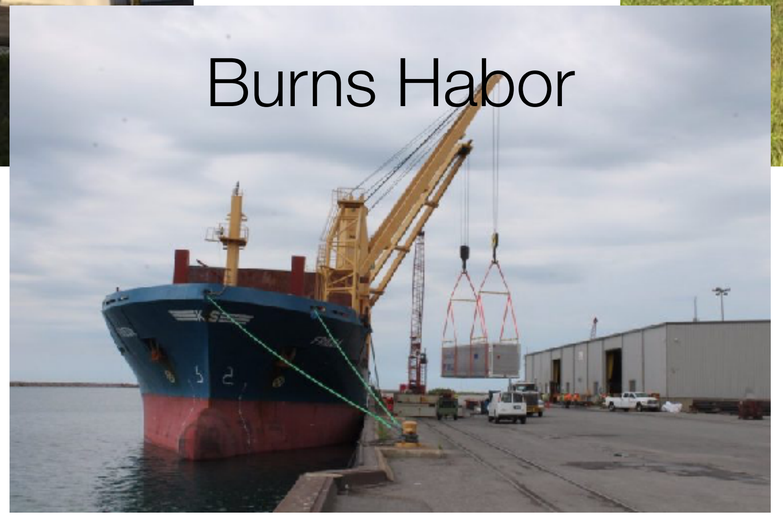
Short baseline programme at Fermilab

- To resolve experimental inconsistencies in the measured ν-spectrum
  - SBND (near detector)
  - MicroBooNE (operating)
  - MiniBooNE
  - refurbished ICARUS arrived at Fermilab



ICARUS Trip

CERN



Burns Habor

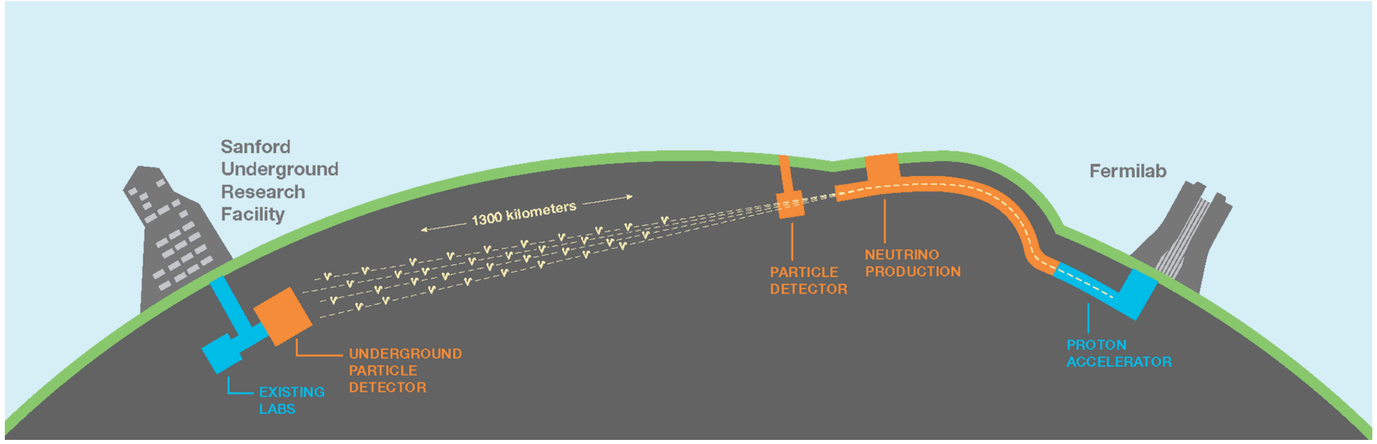
Fermilab

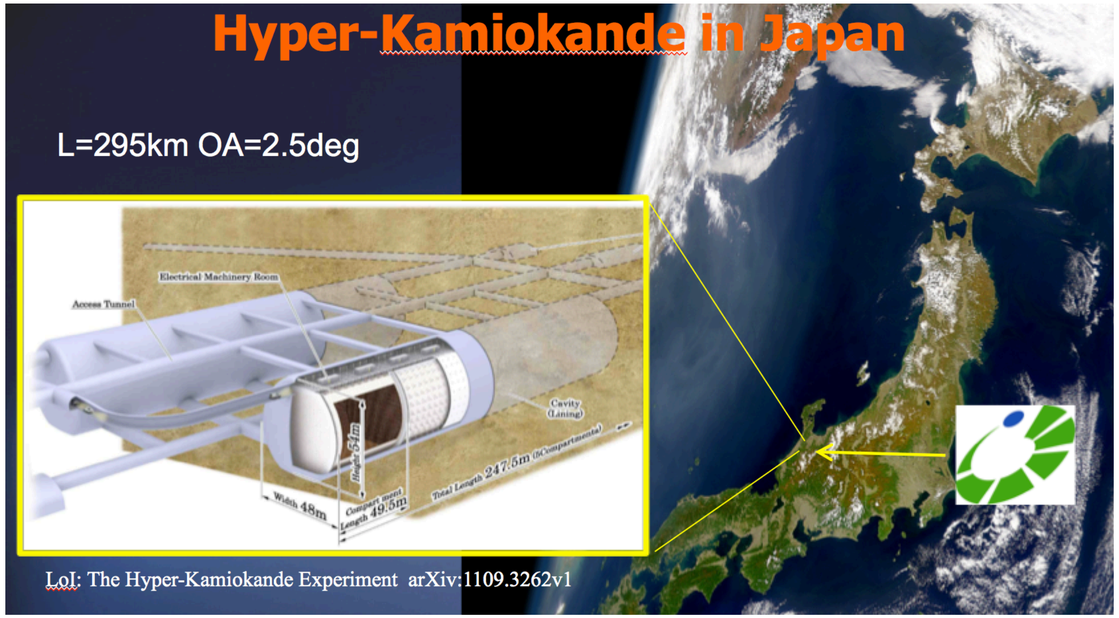
Long baseline neutrino programmes

- Fermilab is planning a long baseline neutrino facility (LBNF), a wide band neutrino beam to the DUNE experiment (LArTPC) in South Dakota

- Tokyo is considering Hyper-K (water Cherenkov detector) at Kamioka

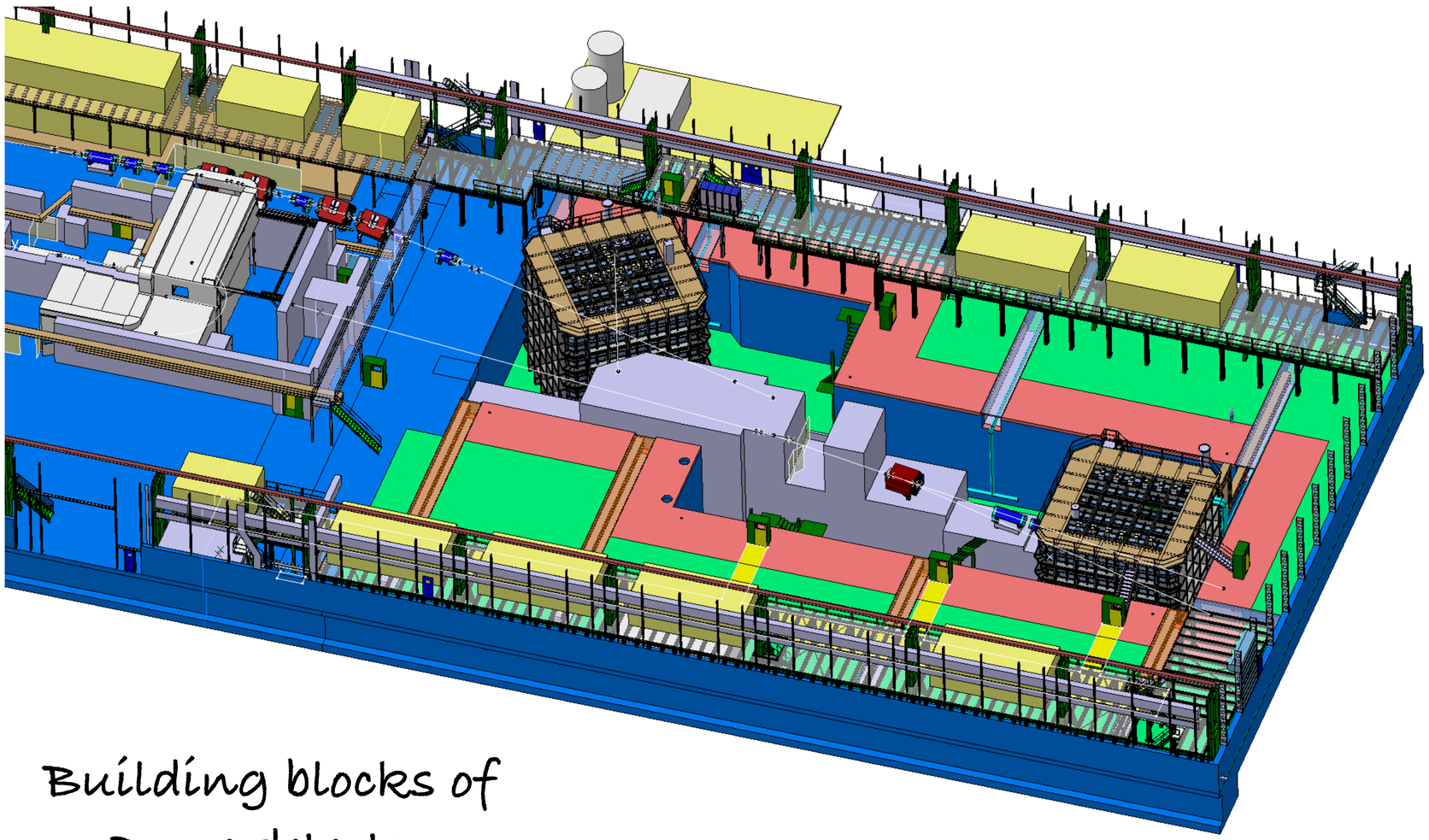
- Goals: neutrino-oscillation parameters, mass hierarchy and CP-violation, …





Neutrino Platform at CERN

To develop experimental techniques, e.g. protoDUNE
– single phase LArTPC
– double phase LArTPC



Building blocks of Dune detector

Preparing the protoDUNE cryostat structures at CERN

preparing the cryostat inner structures

active volume 6x6x6 m^3

at the neutrino platform

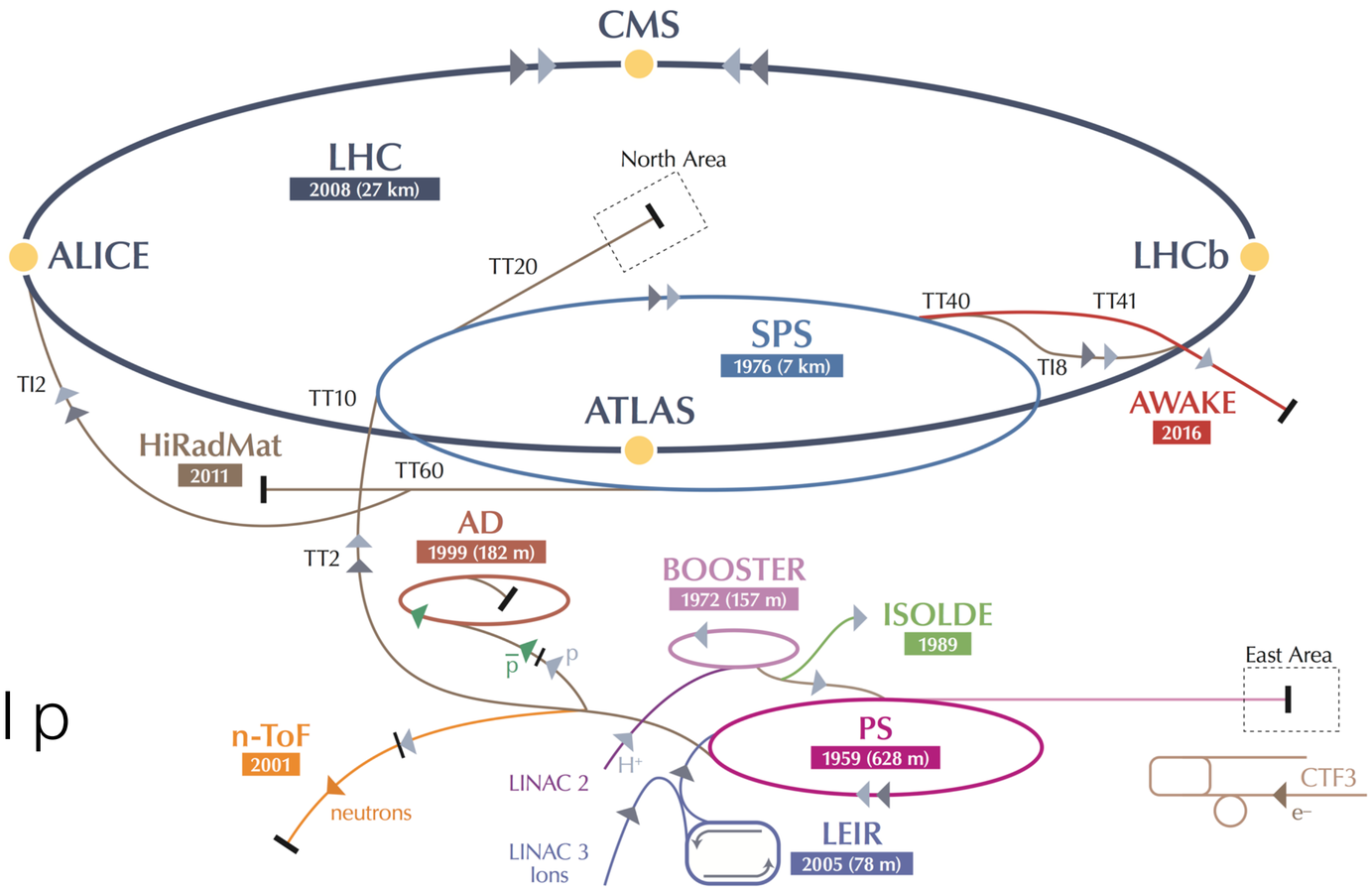
Towards 2020 Update of European Strategy for Particle Physics

– LHC and HL-LHC exploitation (√)
– Prepare for the next step at the energy frontier
– Rich diversity programme…

LHC and its injector chain used for physics

- LHC
  - ongoing Run 2 @ 13 TeV
- Injectors supporting
  - Fixed target programme
  - ISOLDE (isotopes)
  - n-ToF
  - AD-programme

} 75% of all p

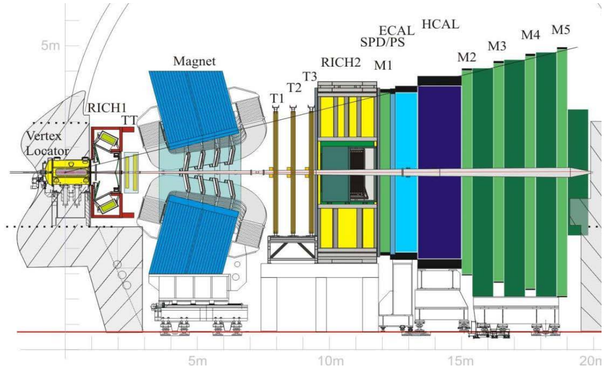


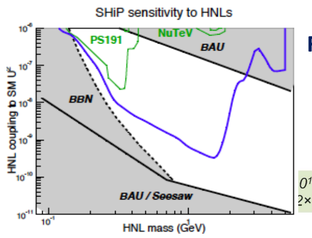
Physics Beyond Collider Study

- Kickoff meeting held in September 2016
  Follow-up in November 2017
  - Study of fixed target programme

…even with LHC beams

SMOG

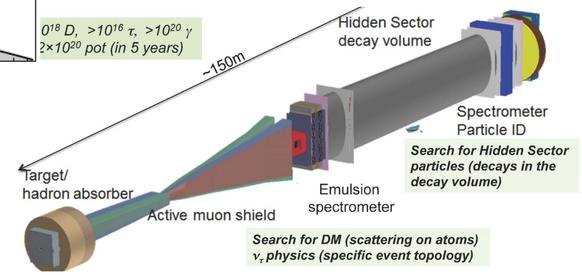




SHiP:
Flagship program for a comprehensive investigation of the Dark Sector in the few GeV domain

Exploits the unique high-E/ high-I SPS features

0^{18} D, $>10^{16}$ τ, $>10^{20}$ γ
2×10^{20} pot (in 5 years)



Search for Hidden Sector particles (decays in the decay volume)

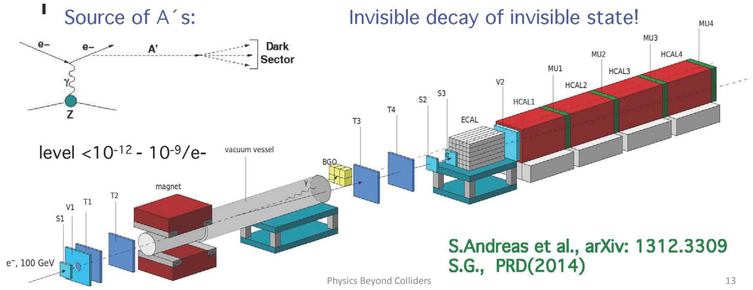
Search for DM (scattering on atoms)
ν_τ physics (specific event topology)

Similar layout as NA62, with larger acceptance to reach the c / b mass range

Beam Dump Facility already under study at CERN

Dark sector search complementary to SHiP: invisible decays from missing energy

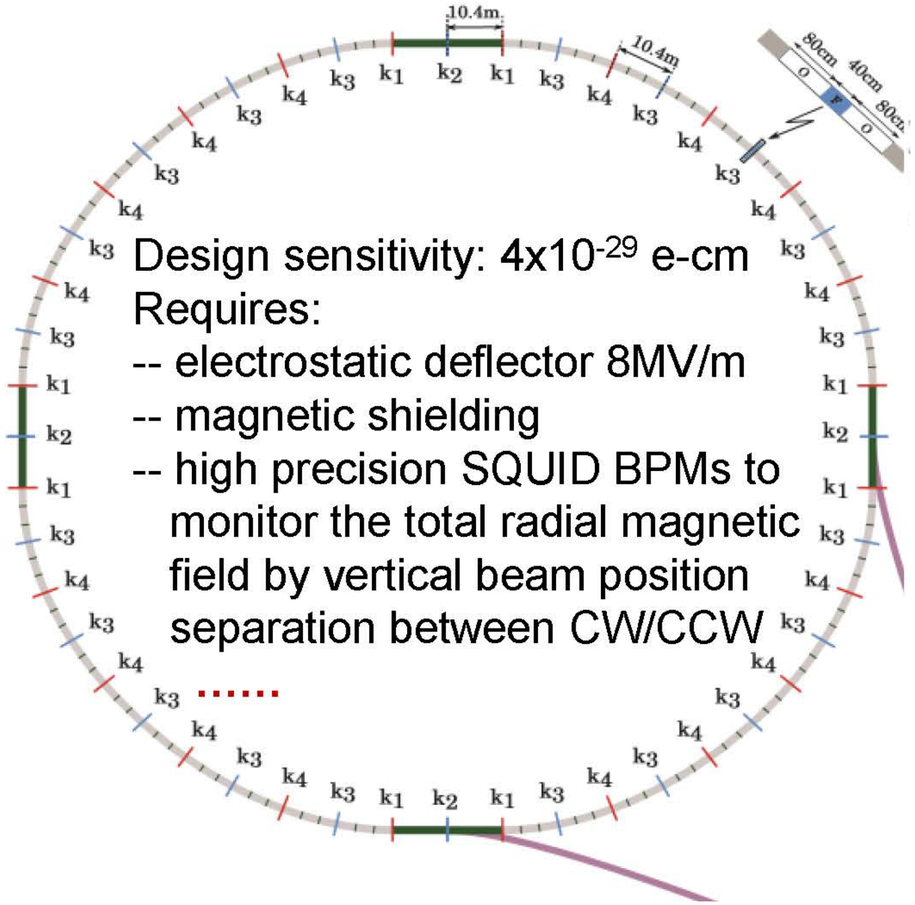
First implementation in 2016 by NA64 on an electron test beam
Wish to extend the method to μ / π / K / p beams
(+ possibly higher intensity e's with AWAKE techno)

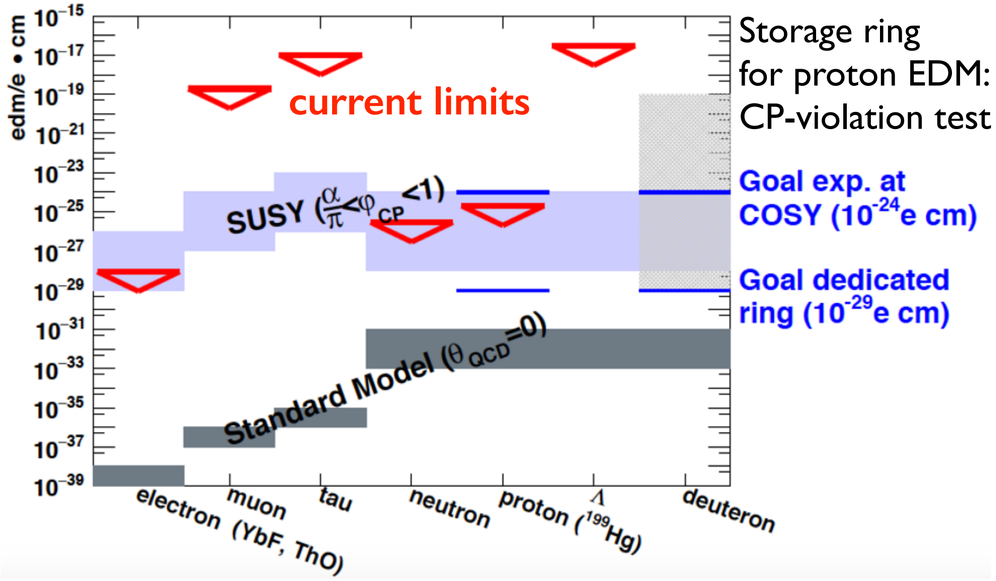


S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

Physics Beyond Collider Study cont'd

Study of an all-electric storage ring





Storage ring for proton EDM: CP-violation test

Goal exp. at COSY (10^{-24} e cm)

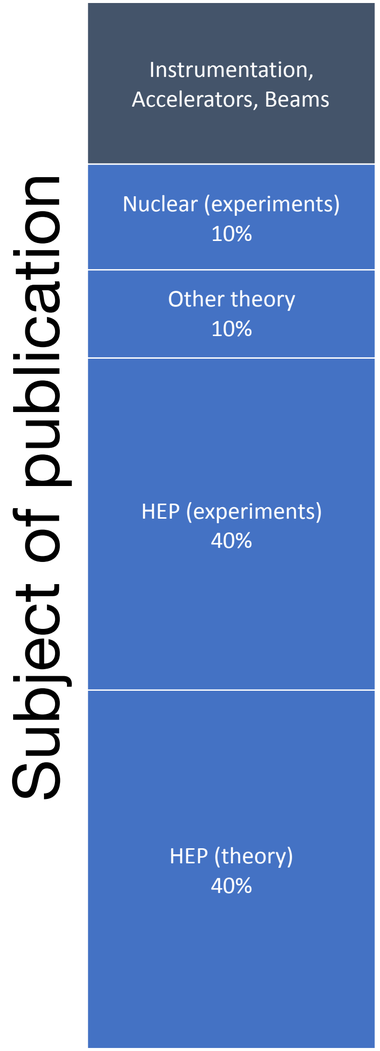
Goal dedicated ring (10^{-29} e cm)

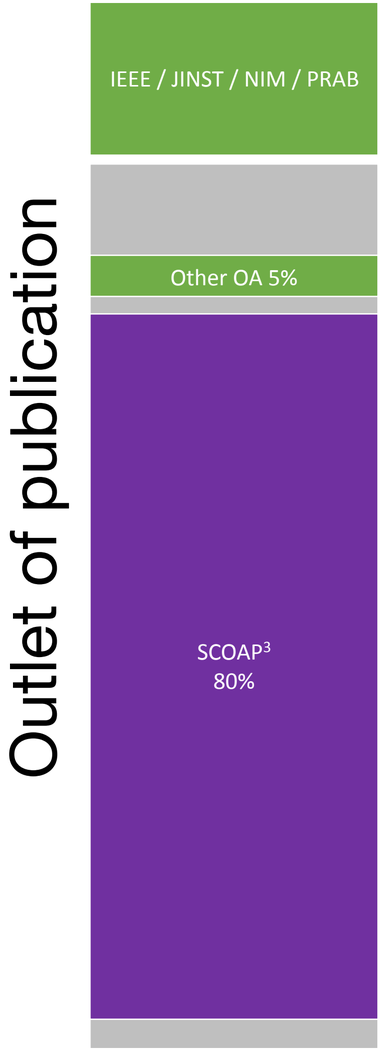
Sensitivity of 10^{-29} e-cm corresponds to 100 TeV for new physics scale

Open Access and SCOAP^3

HEP supporting Golden Open Access Policy

- Open Access has become the Standard for HEP and policy at CERN
  - with APS joining SCOAP^3 some 85% of particle physics publications are covered by golden Open Access status
- Collaborative spirit of HEP community has helped introduce a successful implementation of Golden Open Access





Summary

- Experimental Programme of LHC extremely rich; long range experimental programme guarantees physics return
    - by exploring the highest energies
    - by searching for violations of the SM in (highly sensitive) rare decays
- Preparing Update of the European Strategy for Particle Physics
    - LHC and HL-LHC
    - Energy Frontier
    - Vibrant physics programme beyond colliders

2018 (end): reports on Physics
2019: community discussion
with input from other regions